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CRYOGENIC TENSILE PROPERTIES
OF
SELECTED AEROSPACE MATERIALS

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CRYOGENIC TENSILE PROPERTIES OF SELECTED
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ABSTRACT

Tensile properties data are presented on fifteen materials which were tested at 75°F, -100°F, -320°F and -423°F temperatures. The test equipment utilized to obtain these data and test methods are described. The test results are discussed.

Materials evaluated are:

Titanium Alloys: 5 Al-2.5 Sn ELI
6 Al-4V ELI

Stainless Steels and Iron-Base Alloys: 321, 347C, AM350, A286, 18% Ni maraging steel

Nickel-Base Alloys: Hastelloy C, Inconel X-750, Inconel 713-C

Aluminum Alloys: A356-T6, 2219-T81, 5456-0, 6061-T6, 7079-T6

INTRODUCTION

The information presented in this paper has been compiled from tests performed at Aerojet-General Corporation, both in Sacramento and the Von Karman Center at Azusa. It represents the results of screening and acceptance tests conducted in conjunction with the NERVA program. The tensile properties obtained from these screening tests were utilized in establishing design allowables on materials for different missile components. The following families of materials were investigated:

Titanium (A110-AT-ELI-5 Al 2.5 Sn), C120 AV ELI (6 Al-4V)

Iron-base Alloys (321, 347C, AM350, A286, 18% Ni (250)) Maraging Steel

Nickel-base Alloys: Hastelloy C, Inconel X-750 and 713C

Aluminum Alloys: A350-T6, 2219-T81, 5456-0, 6061-T6 and 7079-T6

Several conditions of some of these materials were evaluated. Ultimate and yield tensile strength, elongation, area reduction, and notched tensile properties were obtained and are presented in tabular form. Data were obtained at room temperature, -100°F, -320°F and -423°F temperatures. The data was obtained utilizing a modified NASA type flat specimen and the R3 type round specimen, as specified in Method 211.1 of Federal Test Method Standard 151A.

EXPERIMENTAL EQUIPMENT

Equipment

All tensile tests were performed on 60,000-lb capacity Baldwin-type hydraulic-operated tensile machines.

For the tests at -100°F and -320°F, a special liquid container was fabricated. The container consisted of two stainless steel beakers of different sizes, which were nested and welded together at the top, forming a double-walled vessel, open at one end. A hole was bored in the bottom of this chamber and the lower specimen-gripping fixture was inserted and welded in place. The chamber between the inner and outer walls was then evacuated and sealed off to provide thermal insulation. The fluid level in the container was maintained three inches above the top of the specimen. Strain measurements were taken by means of an extensometer mounted on the tensile specimen. The extension rods were attached to a differential transformer above the cryogenic fluid, from which strain signals were transmitted to the stress-strain chart on the tensile machine.

Tests at -423°F were conducted in a cryogenic test cell, utilizing a 20,000-lb capacity cryostat. Figure 1 shows the cryostat in position for a tensile test, connected to a 125-liter supply dewar containing liquid hydrogen. Liquid hydrogen enters the cryostat through the flexible vacuum-jacketed tube connected to the lid. Gaseous hydrogen exhausts through the other tube shown. Liquid-level was controlled with the aid of an indicator, consisting of carbon resistors mounted in a rake. Strain measurements were taken by means of a standard room temperature Baldwin averaging extensometer (Model PS3M) modified for cryogenic use. The modification consisted of replacing the rubber-jacketed leadin wires with Teflon-coated wires, and replacing all the carbon-steel parts with ones made of 300-series stainless steel. During one of the test series, strain-type measurements were taken by crosshead movement using a deflectometer, since the standard extensometer was undergoing the above described modification.

Specimens

The materials were tested using modified NASA type flat or the R3 type round specimens. Figure 2 shows the unnotched flat specimen. Figure 3 shows the notched metal specimen, having a stress-concentration factor, K_t, of 6.3. R3 type specimens shown in Figure 4, which have an 0.25 in. diameter gage section, were used because of the low load capacity of the liquid-hydrogen dewar and to allow fabrication of specimens from limited quantities of material.

TEST PROCEDURES

All tensile tests were conducted in accordance with Method 211.1 of Federal Test Method Standard No. 151a, which is essentially identical with ASTM Specification E8-61T. Load as a function of deformation was automatically recorded. Strain-rate used for these tests was 0.05 inch-per-inch-per minute. In the majority of tests, an extensometer was used for strain measurements. In one series of tests at -423°F, during which the extensometer was inoperative, the speed of testing was controlled according to rates of stressing. The stress rates were selected, on the basis of best available information, as those which would be approximately equivalent to the above strain rate.

The properties were determined with the specimens completely submerged in the cryogenic fluid. All specimens were soaked for at least 20 minutes before testing.

SELECTED MATERIALS AND TEST RESULTS

All materials selected for these tests are potential candidate materials for application in different components in a radiation environment. Most of them are being utilized in other rocket engines and have very attractive strength-to-weight ratio or were expected to have good ductility at low temperatures.

a. Titanium Alloys.

Two types of titanium alloys were tested: A110-AT-ELI (5 Al 2.5 Sn) and C120-AV-ELI (6 Al 4V).

(1) A110-AT-ELI (5 Al 2.5 Sn)

Several conditions of this material were tested.

(a) Hot rolled and annealed plates (0.25 in.).

(b) Forged plate (0.5 in.).

(c) Extruded cylinders.

(d) Forged and rolled rings.

(e) Die-forged closures

Material for items (c), (d), and (e) were taken from parts used in the fabrication of a titanium pressure vessel.

Chemical composition of all heats of the titanium materials were made and compared with the specification requirements. The results are shown in Table 1. Average tensile properties for each heat and test temperature are shown in Table 2.

Several interesting comparisons were made possible by the variety of metal working processes used in manufacturing the materials from which specimens were taken.

(a) Plate Materials.

A comparison of hot-rolled with the forged plates at $-423^{\circ}F$ shows that strength and ductility of transverse type specimens are approximately equal. The equivalence of ductility is based on a comparison of area reductions rather than the elongations.

Comparison of hot-rolled plate (transverse specimens) with extruded cylinders (circumferential specimens), all manufactured from the same heat, shows that room temperature tensile, elongation, and area reduction are practically identical in spite of the differences in specimen size and configuration.

(b) Forgings

Comparison of circumferential-type specimens from a ring forging and a closure forging showed that the ring forgings exhibited less ductility at all temperatures. At room temperature, its tensile, yield and notch-ultimate strengths were higher than those of the closure forging. At -100°F, the ring forging had slightly higher tensile and notch-ultimate strengths and equal yield strengths. At -320°F, the tensile and notch-ultimate strengths were equal, but the yield strength of the ring forging was higher. At -423°F, the ring forging had lower tensile strength and yield strength, and equal notch-ultimate strengths. The interesting feature is the crossover range at -320°F and below.

Test results obtained from the closure forging compare very closely with the results obtained on extruded cylinder made from the same heat.

(c) Extruded Cylinders

The tensile properties from all three extruded cylinders in the circumferential direction were very similar.

The notch-ultimate strengths shown for room temperature and -100°F represent variations in K_t, which would account for the different values.

Both longitudinal and circumferential type specimens had properties which were nearly equal. Yield strengths, however, were generally higher for circumferential specimens, and the -423°F notch-ultimate strength for longitudinal specimens at the same K_t was higher by 13,000 psi.

Typical stress-strain curves and stress vs temperature diagrams are shown in Figures 6 through 14.

(2) C-120 AV-ELI (6 Al 4V) Alloy

This alloy has higher ultimate and yield tensile strengths than does A110-AT-ELI, with no evident difference in ductility over the entire range of room to cryogenic temperatures. The notch toughness, however, measured by notched/unnotched ratios (K_t = 6.3), is not quite as high as for the A110 alloy. The tensile properties of 6Al-4V, ELI are nearly the same in the transverse and longitudinal directions over this temperature range.

The data obtained is presented in Table 3 and Figures 15 through 18.

b. Stainless Steels and Iron-Base Alloys

Chemical composition of alloys tested are shown in Table 4, together with the specification limits on the material. Average tensile properties of these alloys are shown in Table 5.

(1) Stainless Steel Type 321

The increase in tensile strength of this material from room to liquid hydrogen temperatures (approx. 65%) is much higher than the increase in the yield strength (approx. 16%). In spite of these strength increases, the ductility, i.e., elongation and area reduction, remained high at -423°F. The notched-ultimate strength at -423°F was much higher than the unnotched yield strength (by a ratio of 2.56) and is indicative of satisfactory notch toughness, in spite of a notched to unnotched ratio of only 0.49. The test results are in agreement with the data reported by NBS.

(2) Stainless Steel Type 347-C (Casting)

The increase in tensile strength (15%) of this alloy, at -423°F, was much less than that obtained for type 321, but the increase in yield strength was much greater (80%). The ductility of the cast specimens reduced drastically with decrease in temperature, as shown by a drop from 30.9% elongation at room temperature to 4% at -423°F. This indicates a strong tendency toward brittle behavior. It should, however, be noted that the notch-ultimate strength at -423°F was still appreciably higher than the unnotched yield strength indicating that the material may still be useful at cryogenic temperatures.

(3) AM350 (SCT)

This material, a martensitic stainless steel, reaches very high ultimate (306,700 psi) and yield strengths (295,000 psi) at -423°F. However, the ductility is greatly reduced and the material becomes so notch-sensitive that it is not considered suitable for cryogenic applications.

(4) Alloy A286, Age Hardened

This material is ideally suited to cryogenic applications. It is an austenitic type material, precipitation hardened to achieve high room temperature strength. At -423°F, the ultimate and yield strengths are appreciably increased above room temperatures values, while ductility remains the same as at room temperature. Note the extreme notch toughness of the materials at -423°F as indicated by the high ratio of notched to unnotched strength.

(5) 18% - Nickel-Maraging Steel (250)

This material represents a series of alloys which have only recently come into general use. Longitudinal and transverse notched and unnotched flat specimens, one-half size, were tested. Although the elongation at -423°F is low, ranging from 2.0 to 4.0%, the yield and ultimate strengths are very high (in the range of 350,000 to 360,000 psi). It should be noted that at -423°F, the ratio of notched ultimate to unnotched yield strength is less than unity (approx. 0.95), so that caution should be used in any low temperature application. Vacuum-melted material, tested transverse to the rolling direction, exhibited significantly higher ultimate and yield strengths than air-melted material, although these properties in the longitudinal direction were essentially equal.

c. Nickel-Base Alloys

Nickel-base alloys, although normally used for high temperature applications, are, as a class, also well suited for cryogenic use. They have good notch toughness and retain their room temperature ductility, while increasing in both tensile and yield strengths. All three of the alloys reported here follow this pattern.

The chemical composition of these alloys, together with the specification requirements, are shown in Table 6. Average tensile properties are shown in Table 7.

(1) Hastelloy C

This alloy, at least in the annealed condition, is suitable for cryogenic applications. The yield strength of this alloy increases more rapidly with decreasing temperature than does the ultimate strength. In spite of this fact, the material retains a comparatively high ductility (28.8% elongation and 35.7% area reduction) at $-423^{\circ}F$.

With a stress concentration factor of $K_t = 6.3$, an actual increase in the notched-unnotched ratio (0.90 vs 0.84) was obtained at liquid hydrogen temperature.

(2) Inconel X-750

This is a precipitation-hardened alloy with high tensile properties at room temperature (171,400 psi tensile, 109,600 psi yield and 26.5% elongation). The percentages of increase in tensile and yield strengths and decrease in ductility from room to liquid hydrogen temperatures are less than those for Hastelloy C. The ratio of notched ultimate to unnotched yield strength remains above unity.

(3) Inconel 713-C

A very small increase in tensile and yield strength of this alloy is observed at liquid hydrogen temperature compared to the corresponding room temperature properties. Note that this alloy appears to be notch-tough, even though the ductility at $-423^{\circ}F$ is quite low (1.3% elongation). This was also noted in the case of cast 347-C stainless steel, and is evidently a characteristic of cast face-centered cubic metals. At -423°F, Inconel 713-C shows a higher yield strength and notched tensile strength than cast 347 and has about the same ultimate strength and ductility. Inconel 713-C is also noticeably stronger at room temperature than cast 347, but much more brittle, as shown by lower elongation and area reduction.

d. Aluminum Alloys

The chemical composition of these alloys compared with the corresponding specifications requirements are shown in Table 8.

Average tensile properties type and condition of material are shown in Table 9.

(1) <u>Alloy A356-T6</u>

The -423°F tensile properties reported fall within the region of values which can be extrapolated from data published by NBS. An increase of more than 20% on the tensile strength and 26% on the yield strength from the respective room temperature data was obtained for liquid hydrogen temperature. The notched-unnotched ratio of ultimate strength is approximately 0.76, indicating that the material is approaching brittle behavior. Caution should be exercised when utilizing this material for cryogenic applications.

A typical stress-strain curve is presented in Figure 19.

(2) <u>Alloy 2219-T81</u>

The tensile properties, at both room temperature and -423°F, coincide with information published by other investigators. This material, although developed for elevated temperature applications, has a combination of high strength and ductility at -423°F, which makes it a useful candidate for cryogenic applications. The data show an increase in ductility, as compared with room temperature data. The notched-unnotched ratio at -423°F is 0.74, although the notched ultimate strength is still above the unnotched yield strength.

(3) <u>Alloy 5456-0</u>

This alloy is non heat-treatable and was tested in the annealed condition. Tensile properties are in good agreement with data from other investigators showing good reproducibility. The notch ultimate strength obtained from these tests is much higher than the unnotched yield strength, indicating satisfactory notch toughness. Note the slight (10%) increase in yield strength and substantial increase (47%) in elongation at -423° as compared to room temperature data. Consequently, this alloy is considered useful for cryogenic applications.

(4) Alloy 6061-T6

The unnotched tensile and yield strength of both plate and forged materials are in close agreement with each other at both room and cryogenic temperatures and closely correspond to the data reported by NBS (Reference 1). The yield and tensile strengths increase approximately 15% and 50%, respectively, when going from room temperature to -423°F. The reduction in area (33.7%) and elongation (11.5%) of the sheet material were appreciably lower than those of forged material (50.7% and 19%, respectively) at room temperature. The notch tensile strength at -423°F was appreciably higher for the forged material. These effects may have resulted, in part, from differences in the specimen size and configuration. Standard size flat specimen were used for the 1/4-inch plate and R3 (subsize) type specimens for the forgings. As in the case of the previous aluminum alloys, high ductility and notch toughness make this alloy suitable for use under cryogenic conditions.

Stress-strain curves and stress vs temperature diagrams are shown in Figures 19 through 21.

(5) Alloy 7079-T6

Although this alloy has seen rather limited use because of welding difficulties and brittle behavior at cryogenic temperatures, its high strength (74,300 psi at room temperature) warranted an evaluation. In addition to the base material, specimens as-welded, welded and heat treated, and aged after welding were tested. The tensile properties for base metal (97,750 psi at -423°F) were lower than those reported by Lewis Research Center for 1/8 in. sheet (115,000 psi, Reference 4), and by General Dynamics for 0.080 in. sheet (112,000 psi) and slightly higher than for 5.0 in. billet material (94,400 psi, Reference 5). These comparisons indicate that the sample geometry had a definite effect on the results The data for the as-welded sheet material (labeled rejectable quality weld) are included for information only. Plate material, which was fully heat-treated after welding, had, as expected, much higher strength and elongation at all temperatures than as-welded material, and between 80 and 92% of the values for parent metal. Welded and heat-treated specimens from forged material exhibited higher strength at all temperatures than did welded plate materials.

The base metal did not appear notch sensitive at temperatures to -300°F, but the welded specimens indicated notch sensitivity below -100°F. The very low ductility of this alloy and the indications of notch sensitivity are significant disadvantages for cryogenic applications.

SUMMARY

Mechanical properties, in particular ultimate tensile and yield strength, notched strength, notch to unnotched ratio, elongation and area reduction for four different families of structural materials were obtained and reported.

In general, most of the materials evaluated are suitable for cryogenic application depending on size and geometry of the part to be utilized in this environment. In selection of material for a particular application, not only the strength characteristic of the material but, to a great deal, the ductility notch sensitivity, shear strength, weld or joint properties, thermal expansion and many other characteristics are required to fully evaluate the suitability of a particular material. Caution should be exercised with materials having low ductility. It is recommended that materials having elongation less than 5% be carefully evaluated before utilizing in cryogenic environment.

Table 1

Chemical Analysis of Titanium Alloys

Alloy Designation		Heat No. Ident	Al	Sn	Fe	C	Mn	V	Others	H_2	O_2	N_2
A-110-AT-ELI (5Al-2.5 Sn)	Specification Limit	Min	4.70	2.0	-	-	-	-	-	-	-	-
		Max	5.60	3.0	0.15	0.08	-	-	-	0.0125	0.12	0.05
	Sample Analysis	D-3272 Plate	5.19	2.30	0.13	0.022	0.006	-		0.0055	0.0312	0.0045
	Sample Analysis	D-3272 Forging	5.05	2.40	0.08	0.012	-	-		0.0048	0.064	0.024
	Sample Analysis	D-3273 Extruded Cylinders	5.12	2.57	0.04	0.04	0.01			0.0058	0.065	0.010
	Sample Analysis	D-3346 Forged Extruded	5.02	2.49	0.07	0.06	-			0.0062	0.066	0.009
	Sample Analysis	V-2096 Forged Plate	5.30	2.50	0.10	0.025	-			0.009	0.080	0.027
C-120 AV, ELI (6Al-4V)	Specification Limit	Min	5.50	-	-	-	-	3.50		-	-	-
		Max	6.50	-	0.10	0.08	-	4.50		0.015	0.13	0.05
	Sample Analysis	D-3067 Forged Plates	6.10		0.07	0.05		4.00		0.0053	0.09	0.017

Table 2

Average Tensile Properties of Titanium Alloys 5Al-2.5 Sn ELI

Material	Temp. °F	Specimen Direction	Ultimate Strength psi	Notch Ultimate Strength, psi	Yield Strength (0.2%) psi	Elongation in 1 in. %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	N-Ult/Un-Y.S.	Number of Tests
A110-AT, ELI (5Al-2.5 Sn)										
1/4" Plate, MDA	RT	(t)	122,500	142,800(K_t= 18.0)	114,400	15.5**	40.0	1.17	1.25	1U, 4N
	-423		219,100	171,000(K_t= 18.0)	205,000*	17.1**	17.8	.78	.84	2U, 4N
1/2" Plate, forged (Heat V-2096)	RT	(t)	124,300	169,400(K_t= 7)	115,600	17.0**	38.2	1.36	1.47	3[illegible]
	-320		192,900	231,200(K_t= 7)	182,500	14.0**	24.7	1.20	1.27	3[illegible]
	-423		214,300	226,000(K_t= 5.8)	203,500	9.8	16.0	1.06	1.11	3[illegible]
1/2" Plate, forged (Heat V-2096)	RT	(l)	126,500	181,200(K_t= 7)	121,000	19.3**	47.3	1.43	1.50	3[illegible]
	-320		198,800	248,000(K_t= 7)	192,000	14.5**	33.2	1.25	1.29	3[illegible]
	-423		221,300	235,000(K_t= 5.7)	218,000	7.5	24.0	1.06	1.08	3U, 2N
Forged Adapter Ring No. 220 (Heat D-3272)	RT	(c)	122,900	167,900(K_t= 7-9)	113,000	14.0	33.6	1.37	1.48	4[illegible]
	-100		143,100	188,800(K_t= 8-9)	130,700	11.0	28.1	1.32	1.44	4[illegible]
	-320		182,700	234,200(K_t= 8-9)	163,500	14.0	24.3	1.28	1.43	5[illegible]
	-423		197,400	234,400(K_t= 7-10)	178,800	10.0	21.8	1.19	1.31	5[illegible]
Forged Closure No. 217 (Heat D3346)	RT	(c)	118,300	157,600(K_t= 9)	107,800	15.0	39.3	1.33	1.46	4[illegible]
	-100		140,600	183,300(K_t= 9)	130,700	14.0	34.5	1.30	1.40	4[illegible]
	-320		182,700	233,700(K_t= 8)	153,500	19.5	34.2	1.28	1.52	4U, 5N
	423		214,000	235,400(K_t= 7-10)	184,400	19.5	21.6	1.10	1.28	
Extruded Cylinder No. 465 (Heat D3346)	RT	(c)	117,300	159,900 (K_t= 6-7)	108,100	16.4	47.5	1.36	1.48	5[illegible]
	-100		136,600	187,100(K_t= 6-7)	125,000	14.0	35.1	1.37	1.50	5[illegible]
	-320		181,800	233,600(K_t= 6-8)	166,700	11.6	35.6	1.28	1.40	5[illegible]
	-423		207,200	236,200(K_t= 6-8)	190,800	13.5	19.2	1.14	1.24	5[illegible]
Extruded Cylinder No. 218 (Heat D 3273)	RT	(c)	124,100	235,400(K_t= 7-10)	114,200	15.0	43.7	1.90	2.06	5[illegible]
	-100		142,200	195,300(K_t= 7-8)	131,400	13.0	37.3	1.37	1.49	5[illegible]
	-320		185,000	240,200(K_t= 8)	171,800	21.0	33.6	1.30	1.40	5[illegible]
	-423		205,800	238,900(K_t= 7-10)	192,200	13.6	29.0	1.16	1.24	5[illegible]
Extruded Cylinder No. 219 (Heat D3273)	RT	(c)	122,200	164,800(K_t= 7-9)	111,400	14.0	40.3	1.35	1.48	5[illegible]
	-100		141,400	188,100(K_t= 6-10)	130,200	12.0	33.8	1.33	1.45	5U, 4N
	-320		183,400	238,600(K_t= 7-9)	173,700	17.0	35.6	1.30	1.38	5[illegible]
	-423		208,200	237,800(K_t= 7-10)	190,800	13.3	21.8	1.14	1.25	5[illegible]
Extruded Cylinder No. 219 (Heat D3273)	RT	(l)	119,900	165,100(K_t= 8-9)	107,500	15.0	43.6	1.38	1.54	5[illegible]
	-100		139,300	186,700(K_t= 8-9)	123,800	12.0	34.8	1.34	1.51	5[illegible]
	-320		187,500	239,500(K_t= 7-9)	167,000	15.0	36.5	1.28	1.43	5[illegible]
	-423		211,200	253,300(K_t= 8-10)	198,600	13.6	22.6	1.20	1.28	5[illegible]

*Based on strain estimated from crosshead travel of tensile machine.

**Elongation in 2" (t) transverse, (l) longitudinal, (c) circumferential.

Table 3

Average Tensile Properties of C120-AV-ELI

6Al-4V, ELI 1/2" Plate, forged (Heat B9067)	RT	(l)	140,600	158,300 (K_t = 6-7)	133,000	14.0	39.8	1.41	1.47	30
	-100		167,900	226,100 (K_t = 5-6)	162,100	13.0	30.8	1.35	1.39	30
	-320		227,000	276,100 (K_t = 4-6)	214,400	10.7	31.3	1.22	1.29	30
	-423		239,000	264,000 (K_t = 6)	220,000	11.0	24.8	1.10	1.16	30
1/2" Plate forged (Heat B9067)	RT	(t)	138,800	188,900 (K_t = 7-8)	132,700	14.7	43.7	1.36	1.42	30
	-100		162,600	214,800 (K_t = 7)	156,900	13.3	35.3	1.38	1.37	30
	-320		216,900	259,000 (K_t = 6-8)	207,100	11.0	30.2	1.19	1.25	30
	-423		239,000	284,000 (K_t = 6-8)	231,000	6.0	22.3	.94	.97	30

Table 4

Chemical Analysis of Stainless Steel and Iron Base Alloys

Material Designation			C	Cr	Mo	Mn	Si	S	P	Cb	Ta	Al	Ti	Cu	Fe	Others	Ni	H_2 ppm	O_2 ppm	N_2 ppm
321	Specification Limit	Min.	-	17.00	-	-	0.40	-	-			-	5xC	-	Bal.		8.00			
		Max.	0.08	19.00	0.50	2.00	1.00	0.03	0.04	-	-	-	0.70	0.50	Bal.		11.00			
	Sample Analysis		0.049	17.80		1.80	0.54	0.013	0.015	-	-	0.07	0.57	0.37	Bal.		10.3	100	10	8
347-c Sand Casting	Specification Limit	Min.	-	17.00	-	-	-	-	-	10xC	-		-	-	Bal.		9.00			
		Max.	0.10	20.00	0.50	2.00	1.50	0.04	0.04	1.35	-	-	-	0.50	Bal.		12.00			
	Sample Analysis		0.08	19.30	0.28	1.09	1.00	0.018	0.016	1.85	0.21	-	0.75	0.31	Bal.		9.35	15	690	110
AM-350	Specification Limit	Min.	0.08	16.00	2.50	0.50	-	-	-						Bal.	0.07 N_2	4.00			
		Max.	0.12	17.00	3.25	1.25	0.50	0.03	0.04						Bal.	0.13 N_2	5.00			
	Specimen Analysis		0.08	16.73	2.78	0.75	0.32	0.009	0.02						Bal.	0.113 N_2	4.28	6	290	1130
A-286	Specification Limit	Min.	-	13.50	1.00	1.00	0.40	-	-			-	1.90		Bal.	0.001 B	24.00			
		Max.	0.08	16.00	1.50	2.00	1.00	0.03	0.04			0.35	2.30		Bal.	0.01 B	27.00			
	Specimen Analysis		0.061	14.87	1.15	1.11	0.77	0.005	0.01			0.26	2.05		Bal.		25.63	-	5	7
18% Ni Maraging Steel (Preliminary Data)	Specification Limit (Tentative)	Min.	0.01	-	4.6	-	-	-	-			-	0.30		Bal.	7.0 Co*	17.00			
		Max.	0.03		5.1	0.10	0.10	0.01	0.01			0.1	0.50			8.0 Co	19.00			
	Specimen Analysis																			

*Others Continued: 0.003 max. B; 0.02 max. Zr; 0.05 max. Ca

Table 5

Average Tensile Properties of Stainless Steel and Iron Base Alloys

Alloy	Temp. °F	Ultimate Strength psi	Notch Ultimate Strength, psi	Yield Strength (0.2%) psi	Elongation in 2 in. %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	N-Ult/Un-Y.	Number of Tests
Type 321	RT	81,850	84,300(K_t=6.3)	34,350	58.3	65.4	1.04	2.45	2U, 3N
	-423	216,700	106,300	57,000*	30.3	51.7	0.49	1.87	2 ●
Type 347-c Cast	RT	85,600	71,300(K_t=6.3)	39,900	30.9	85.4	0.83	1.79	4U, 3N
	-423	113,500	102,300	84,000*	4.3	5.1	0.90	1.22	2 ●
AM350-SCT (850°F)	RT	200,050	211,300(K_t=6.3)	161,100	9.3	33.5	1.05	1.31	2U, 4N
	-423	306,700	80,900	295,000*	1.5	0.9	0.26	0.27	2 ●
A-286	RT	155,650	152,900(K_t=6.3)	106,150	19.8	33.9	0.98	1.[illegible]	2U
	-423	216,600	202,500	141,000*	24.5	32.2	0.95	.43	
18% Ni Maraging Steel "V-long"	-423	356,000	322,300(K_t=6.3)	347.50	2.3**	-	0.9[illegible]	0.95	2U, 3N
"V-transv" (0.09" sheet)		365,000	328,000	350,500	2.8**	-	0.9[illegible]	0.94	2U, 3N
"A-long"	-423	356,000	323,300(K_t=6.3)	344,000	3.0**	-	0.91	0.94	1U, 3N
"A-transv"		345,000	321,000	339,000	3.5**	-	0.95	0.95	2U, 3N
3/8-in. Dia. bolting	-423	335,000	-	-	-	-	-	-	3 ●
peened bolting		380,000	-	-	-	-	-	-	3 ●

*Based on strain estimated from crosshead travel of tensile machine.

**Elongation in 1".

"A" Air melted.

"V" Vacuum remelt of "A".

Table 6

Chemical Analysis of the Nickel Base Alloys

Material Designation			Ni	C	Cr	Fe	S	Si	Cu	Mn	Mo	Co	P	Ti	Al	Others	H_2 ppm	O_2 ppm	N_2 ppm
Hastelloy C	Specification	Min.	Bal.	-	14.50	4.00	-	-		-	15.00	-	-			3.00 W			
				0.08	16.50	7.00	0.05	1.00		1.00	17.00	2.00	0.04			4.50 W 0.35V			
	Specimen Analysis		Bal.	0.05	15.75	5.46	0.012	0.63		0.55	15.78	1.44	0.008			4.90W 0.26V	5	980	120
Inconel X-750	Specification Limit	Min.	70.00	-	14.00	5.00	-	-	-	-		-	-	2.25	0.40	0.70 Nb			
		Max.	-	0.08	17.00	9.00	0.01	0.50	0.50	1.00		1.00	-	2.75	1.00	1.20 Nb			
	Specimen Analysis		73.44	0.04	14.98	6.64	0.007	0.34	0.05	0.54	-	1.00	-	2.45	0.61	0.82 Nb+Ta 1.1	83	1	3
Inconel 713-C	Specification Limit	Min.	Bal.	0.08	12.00	-	-	-	-	-	3.80	-		0.50	5.50	0.005 B 1.80 Nb+Ta 0.05 Zr			
		Max.		0.20	14.00	2.50	0.015	0.50	0.50	0.25	5.20	1.0		1.00	6.50	0.015 B 2.80 Nb+Ta 0.15 Zr			
	Specimen Analysis		Bal.	0.13	12.86	0.85	0.007	0.16	0.05	0.02	4.51	0.73	0.73	6.22		2.31 Nb+Ta 0.140 Zr 0.010 B			

Table 7

Average Tensile Properties of Nickel Base Alloys

Alloy	Temp. °F	Ultimate Strength psi	Notch Ultimate Strength, psi	Yield Strength (0.2%) psi	Elongation in 2 in. %	Reduction in Area, %	Notched to Unnotched Ratios: N-Ult/Un-Ult	Notched to Unnotched Ratios: N-Ult/Un-Y.S.	Number of Tests
Hastelloy C	RT	118,900	99,700 (K_t=6.3)	59,250	46.3	57.0	.84	1.68	2U, 4N
	-423	172,150	155,550	110,000*	28.8	35.7	.90	1.41	2 [illegible]
Inconel X-750	RT	171,400	163,300 (K_t=6.3)	109,600	26.5	42.5	.95	1.49	2 [illegible]
	-423	217,300	189,300	134,000*	24.8	32.2	.87	1.41	2U, 1N
Inconel 713-C (investment cast)	RT	104,800	116,800	99,850	2.0	3.6	1.11	1.17	2U, 4N
	-423	111,750	127,700	108,000*	1.3	4.9	1.14	1.18	2U, 4N

*Based on strain estimated from crosshead travel of tensile machine.

Table 8

Chemical Analysis of Aluminum Alloys

Alloy Designation			Cu	Si	Fe	Mg	Mn	Cr	Zn	Ti	Others*	H_2 ppm	O_2 ppm	N_2 ppm
A 356-T6	Specification	Min.	-	6.50	-	0.20	-	-	-	-	-			
	Limit	Max.	0.20	7.50	0.20	0.40	0.10	-	0.10	0.20	0.15			
	Sample Analysis		0.02	7.34	0.15	0.30	Nil	-	Nil	0.14		-	-	-
2219-T81	Specification	Min.	5.80	-	-	-	0.20	-	-	0.02	-			
	Limit	Max.	6.80	0.20	0.30	0.02	0.40	-	0.10	0.10	0.15			
	Sample Analysis		5.5	0.08	0.20	Nil	0.25	-	-	-	0.09V	4	1	17
5456-0	Specification	Min.	-	-		4.70	0.50	0.05	-	-	-			
	Limit	Max.	0.10	0.50 (Si+Fe)		5.50	1.00	0.20	0.25	0.20	0.15			
	Sample Analysis		0.08	0.06	0.20	5.29	0.70	0.11	0.04	.085	-	77	1	16
6061-T6	Specification	Min.	0.15	0.40	-	0.80	-	0.15	-	-	-			
	Limit	Max.	0.40	0.80	0.70	1.20	0.15	0.35	0.25	0.15	0.15			
Sheet	Sample Analysis		0.24	0.54	0.50	0.90	0.03	0.20	0.03	0.088		30	1	7
Forging	Sample Analysis		0.34	0.61	0.28	0.85	0.05	0.16	0.12	0.06	0.02Ni			
7079-T6	Specification	Min.	0.40	-	-	2.90	0.10	0.10	3.80	-	-			
	Limit	Max.	0.80	0.30	0.40	3.70	0.30	0.25	4.80	0.10	0.15			
	Sample Analysis		Not Available											

*Range shown refers to 0.05 max. for each other element and a total of 0.15% max.

Table 9

Average Tensile Properties of Aluminum Alloys

Alloy	Temp. °F	Ultimate Strength, psi	Notch Ultimate Strength, psi	Yield Strength (0.2%), psi	Elongation in 2 in., %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	N-Ult/Un-Y.S.	Number of Tests
A-356-T6 Cast (0.125" Specimen)	RT	30,600	29,200(K_t=6.3)	23,000	3.2	2.4	0.95	1.23	4
	-423	48,100	56,350(K_t=6.3)	42,000	2.0	1.8	0.76	0.87	2
2219-T81 (0.125" Specimen)	RT	64,100	61,000(K_t=6.3)	49,800	8.5	20.5	0.95	1.22	1U, 4N
	-423	94,600	70,100(K_t=6.3	70,000*	13.0	25.6	0.74	1.00	2
5456-0 (0.125" Specimen	RT	50,900	48,100(K_t=6.3)	26,500	16.8	26.1	0.94	1.8	2U, 4N
	-423	85,100	44,500	30,500*	24.8	25.4	0.52	1.46	2
6061-T6, Plate (0.125" Specimen)	RT	44,950	44,000(K_t=6.3)	41,900	11.5	33.7	0.98	1.05	2U, 4N
	-423	71,950	61,000	52,500*	23.8	33.7	0.86	1.16	2
forged ring (R-3 Specimen)	RT	44,800	63,000(K_t=8.0)	40,600	19.[illegible]	50.7	1.40	1.55	4
	-100	50,125	67,200	43,800	19.0	50.3	1.32	1.53	4
	-320	63,400	78,700	46,400	24.0	37.1	1.24	1.70	4
	-423	66,400	81,200	52,900	23.1	35.3	1.22	1.53	4
7079-T6 forged ring welded & re-heat treated (0.375" dia. spec.)	RT	74,300	--	65,000	6.3	20.5	--	--	2
	-100	74,450	--	66,100	4.5	17.5	--	--	4
	-300	78,370	--	73,400	1.1	4.8	--	--	4
1/4" base metal plate	-100	80,600	82,600(K_t=6)	69,300	9.5	--	1.02	1.19	1
	-300	90,100	82,400	77,200	6.0	--	0.9[illegible]	1.07	2
	-423	97,750	79,195	--	5.0	--	0.81	--	1U, 2N
1/4" plate welded & re-heat treated	RT	68,060	67,900(K_t=6)	59,775	3.9	--	0.99	1.13	8U, 5N
	-100	72,500	67,940	63,850	4.0	--	0.94	1.05	2U, 7N
	-300	76,000	64,740	69,150	2.2	--	0.85	0.94	3U, 7N
	-423	78,460	59,300	--	2.7	--	0.76	--	3U, 9N
Rejectable quality weldments 0.1875" sheet, as welded	RT	49,000	48,000(K_t=6)	38,700	1.5	--	0.98	1.24	1
	-100	41,300	43,700	41,300	2.0	--	1.06	1.06	1
	-300	49,100	44,700	48,200	3.0	--	0.91	0.93	1
	-423	52,400	36,500	--	2.0	--	0.70	--	1U, 2N
0.1875" sheet, welded & aged	RT	48,400	53,000(K_t=6)	45,800	1.0	--	1.09	1.1[illegible]	1
	-100	62,800	67,800	51,200	3.0	--	0.62	0.76	1
	-300	67,300	41,500	54,700	3.0	--	0.62	0.76	1
	-423	--	34,625	--	--	--	--	--	1

*Based on strain estimated from head-travel of tensile machine.

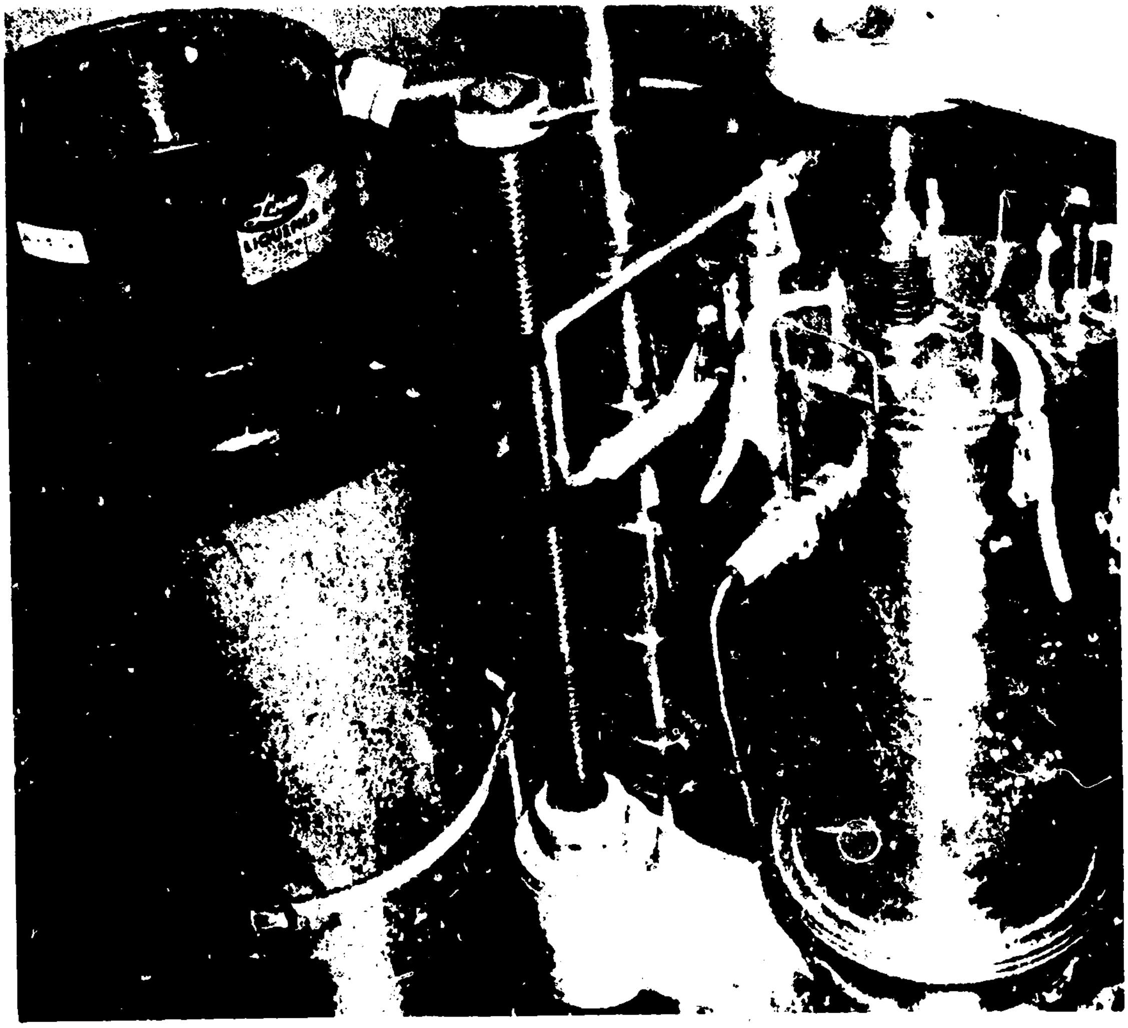

Figure 1

Liquid Hydrogen Cryostat
and Supply Dewar

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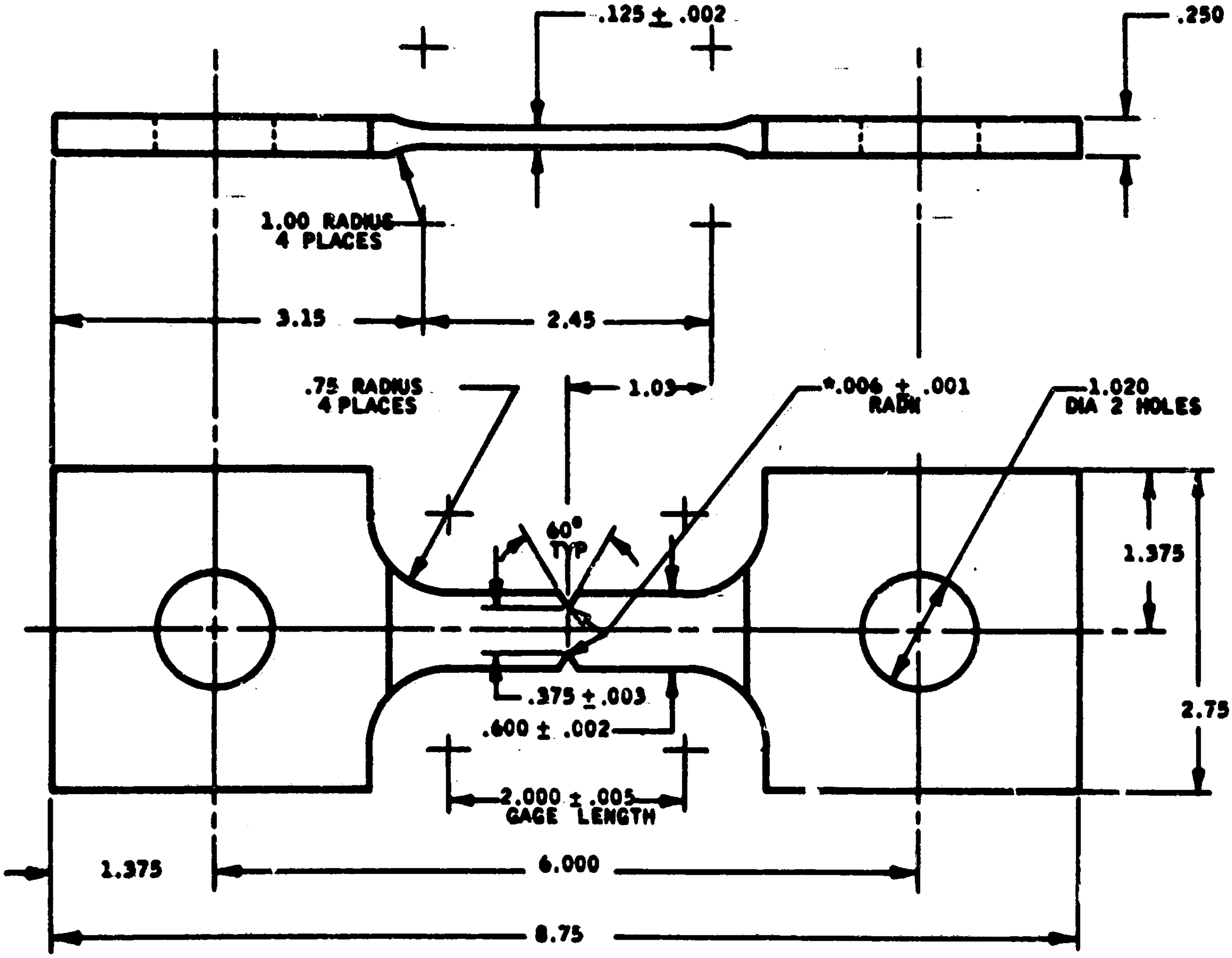


Notched Specimen, Sheet Material

Figure 2

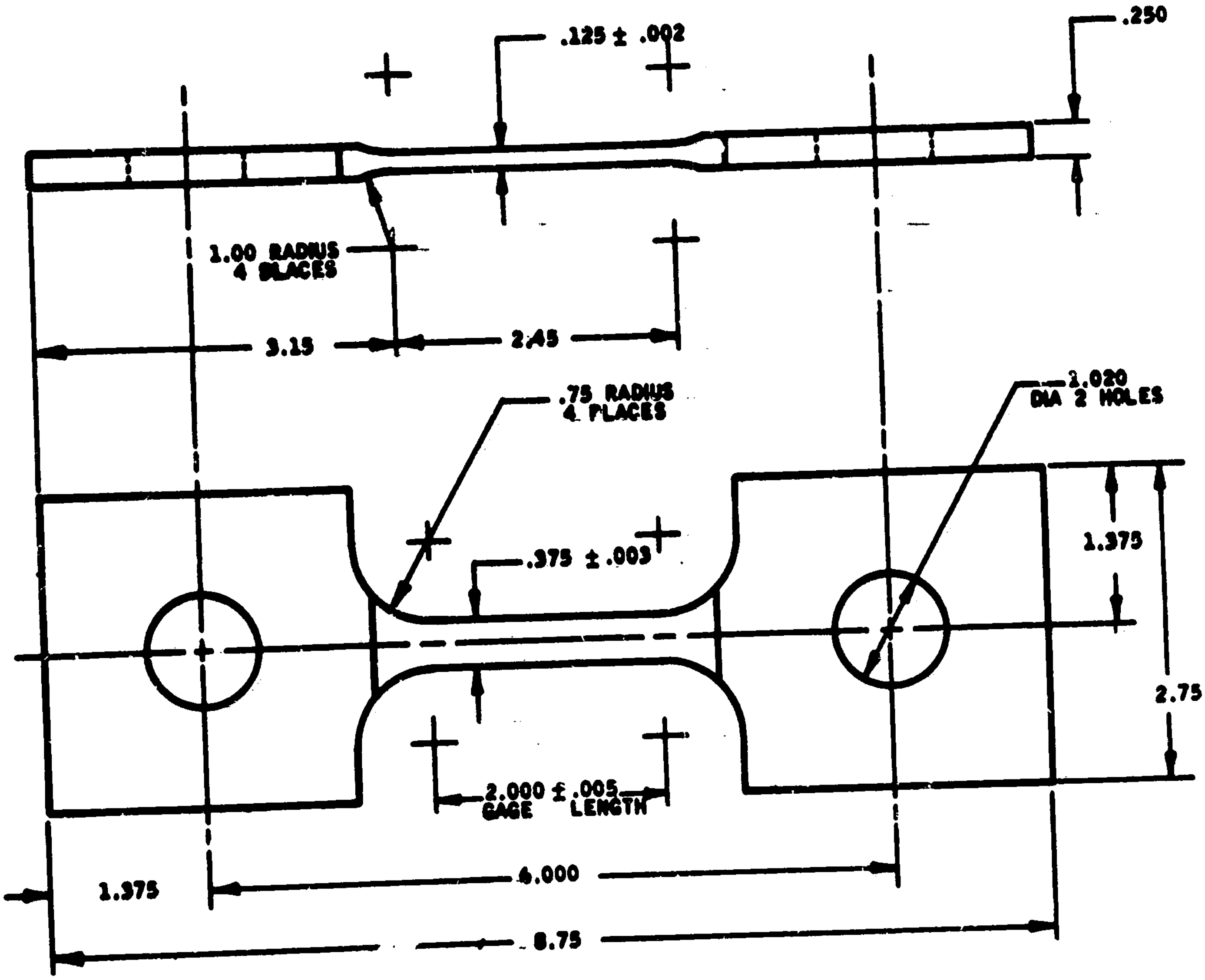
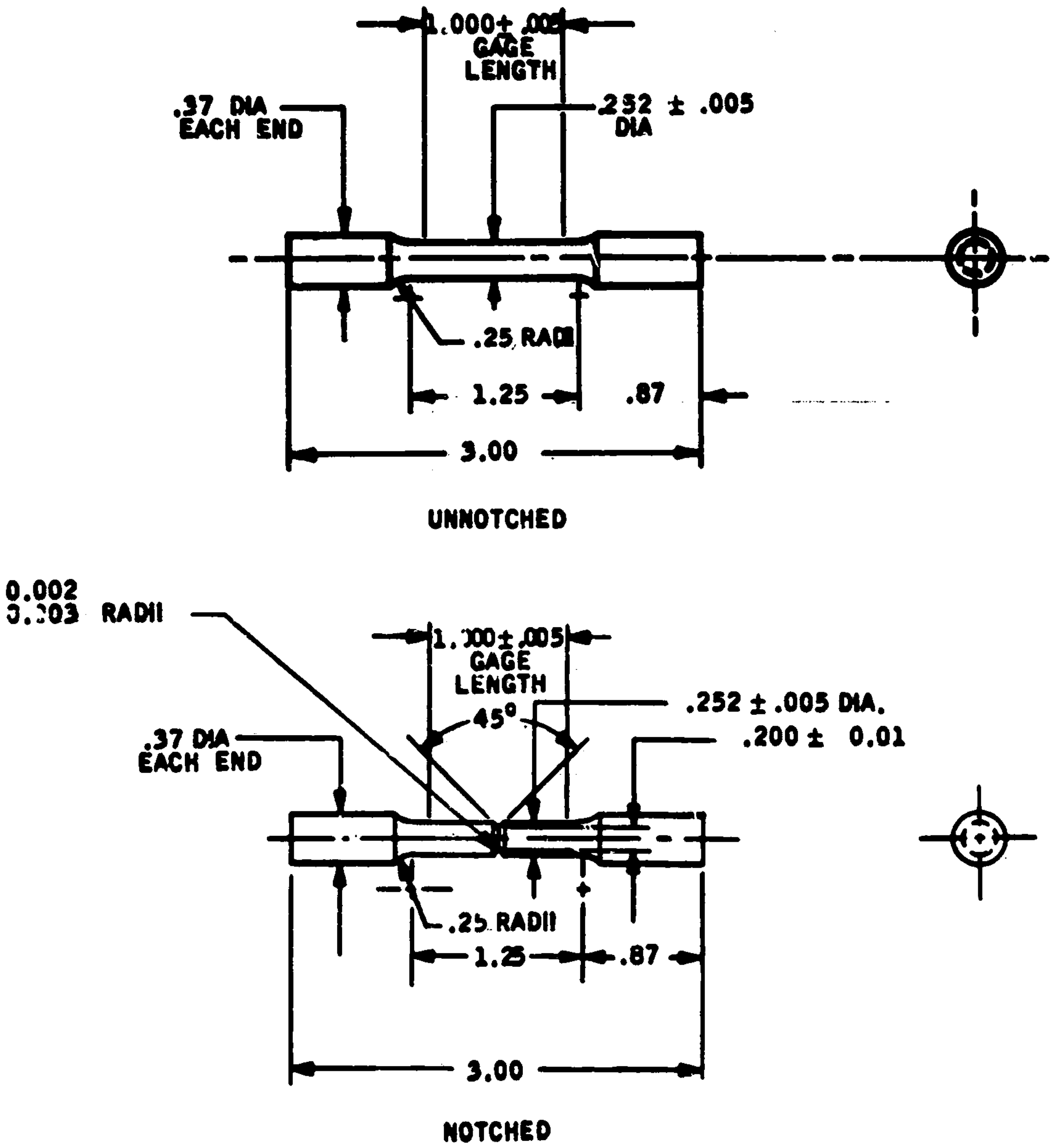


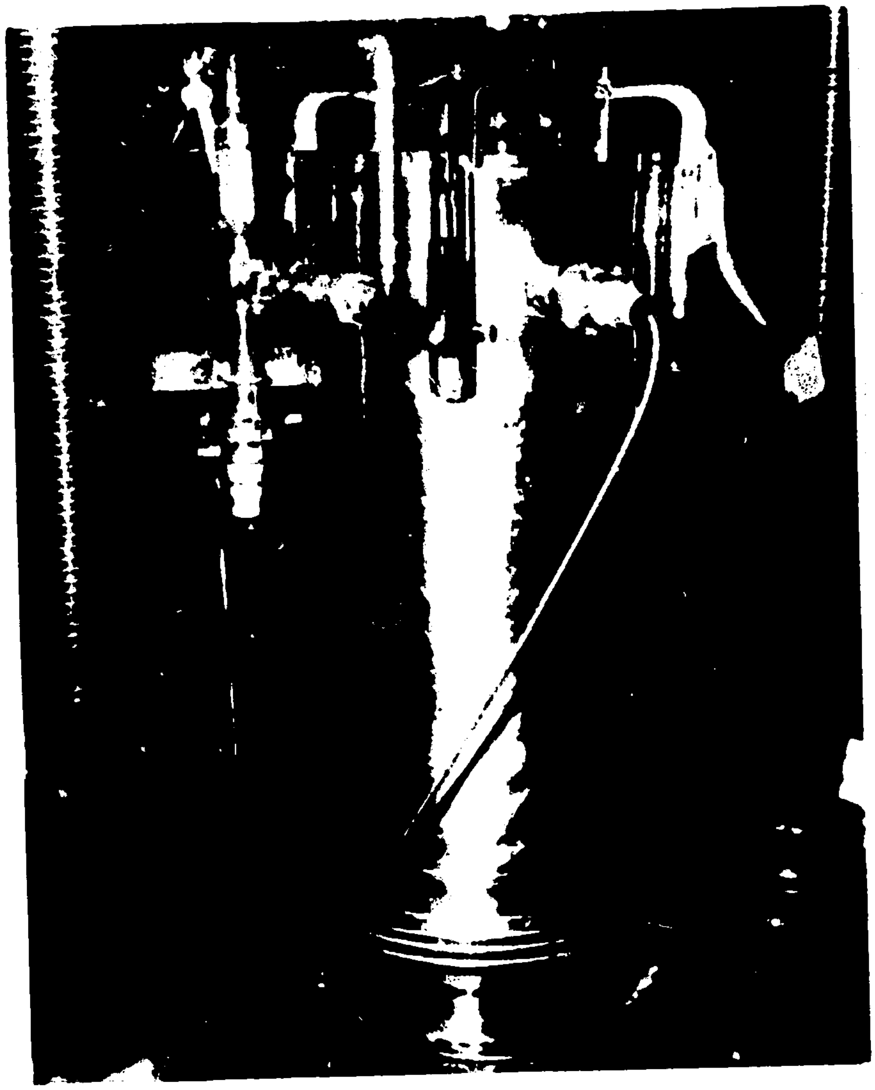
Figure 3

Unnotched Specimens,
Sheet Material



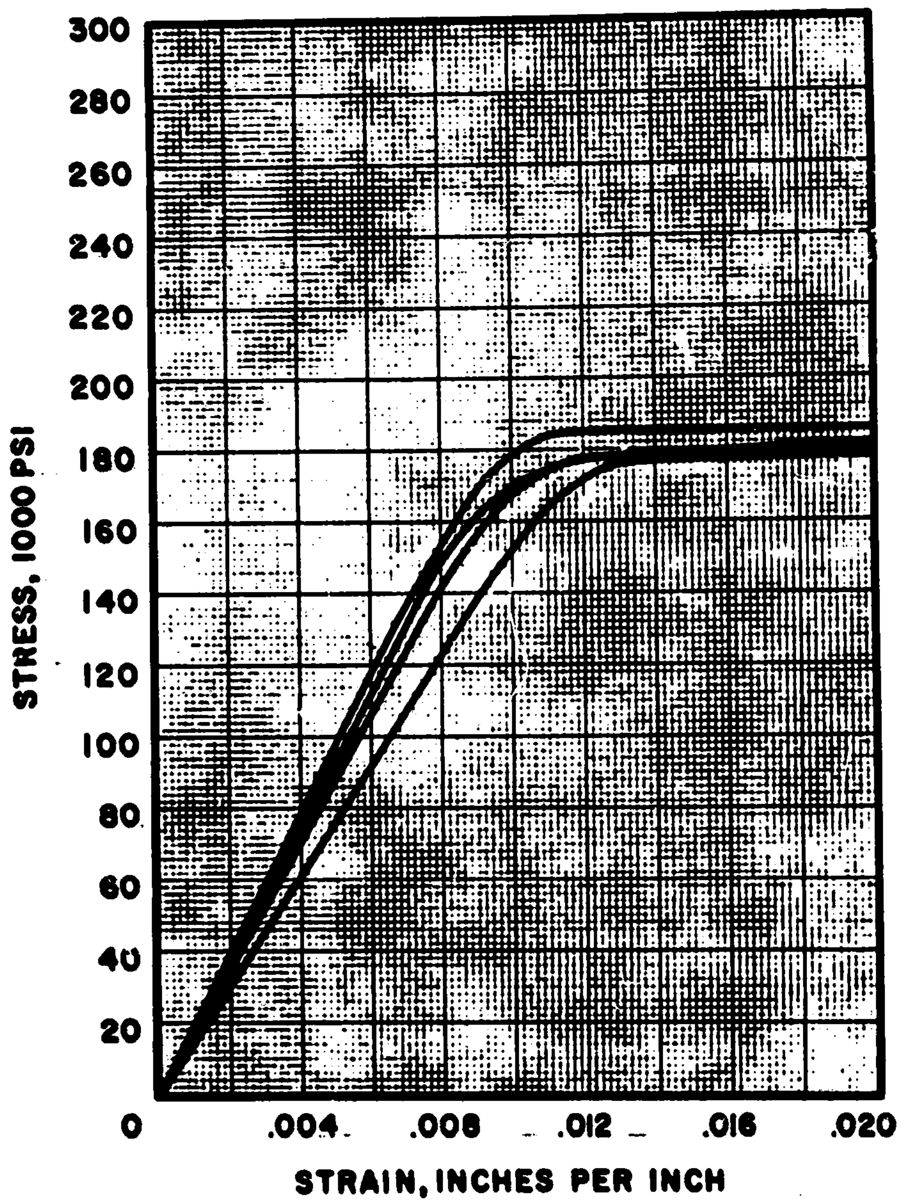
Round Specimen Type R3
Unnotched and Notched

Figure 4



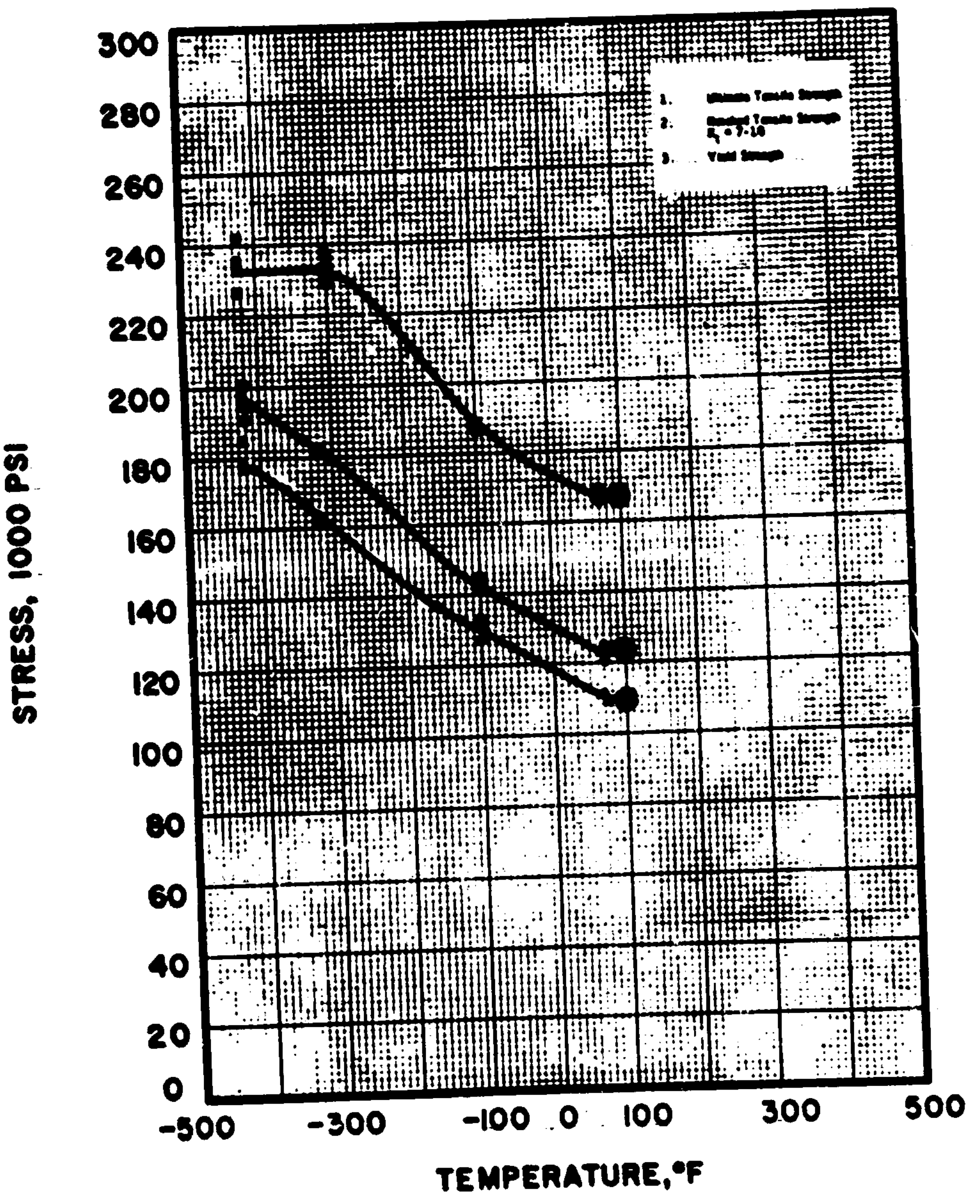
Closeup of Liquid Hydrogen
Cryostat

Figure



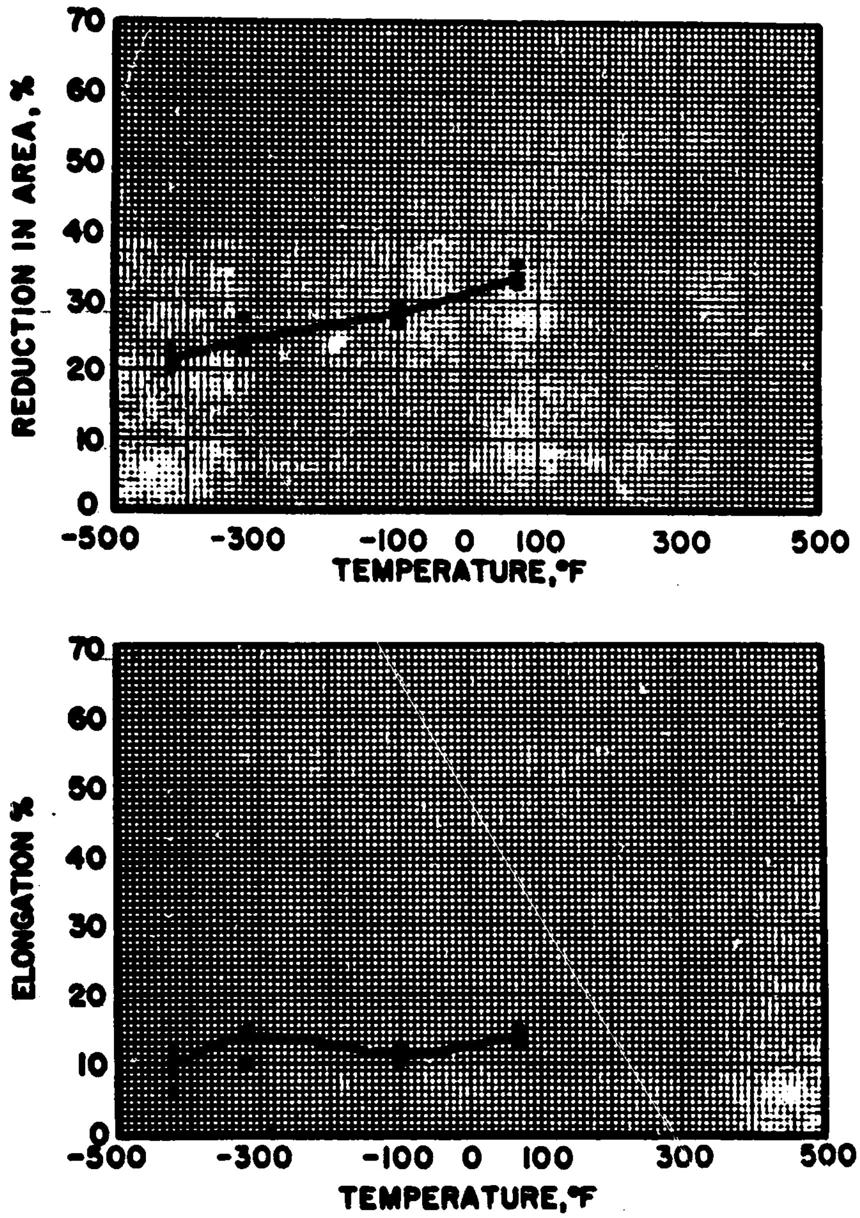
Titanium Alloy A-110-AT-ELI Forging (Heat D3272 — Ring No. 220), Stress-Strain Diagram at -423°F

Figure 6



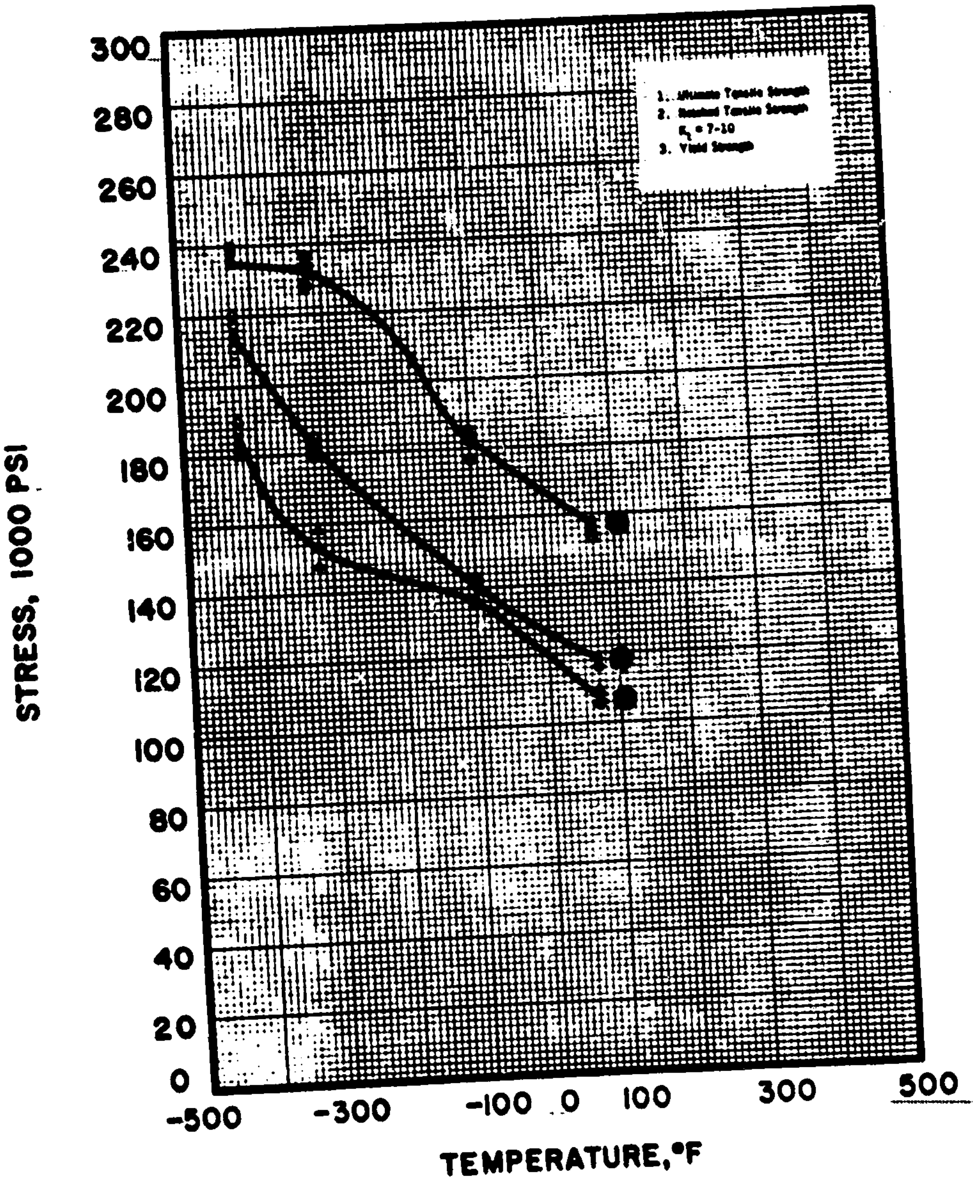
Titanium Alloy A-110-AT-ELI Forging (Heat D3272 Ring No. 220)
Tensile Ultimate, Yield, and Notched Strength as a Function of Temperature

Figure 7



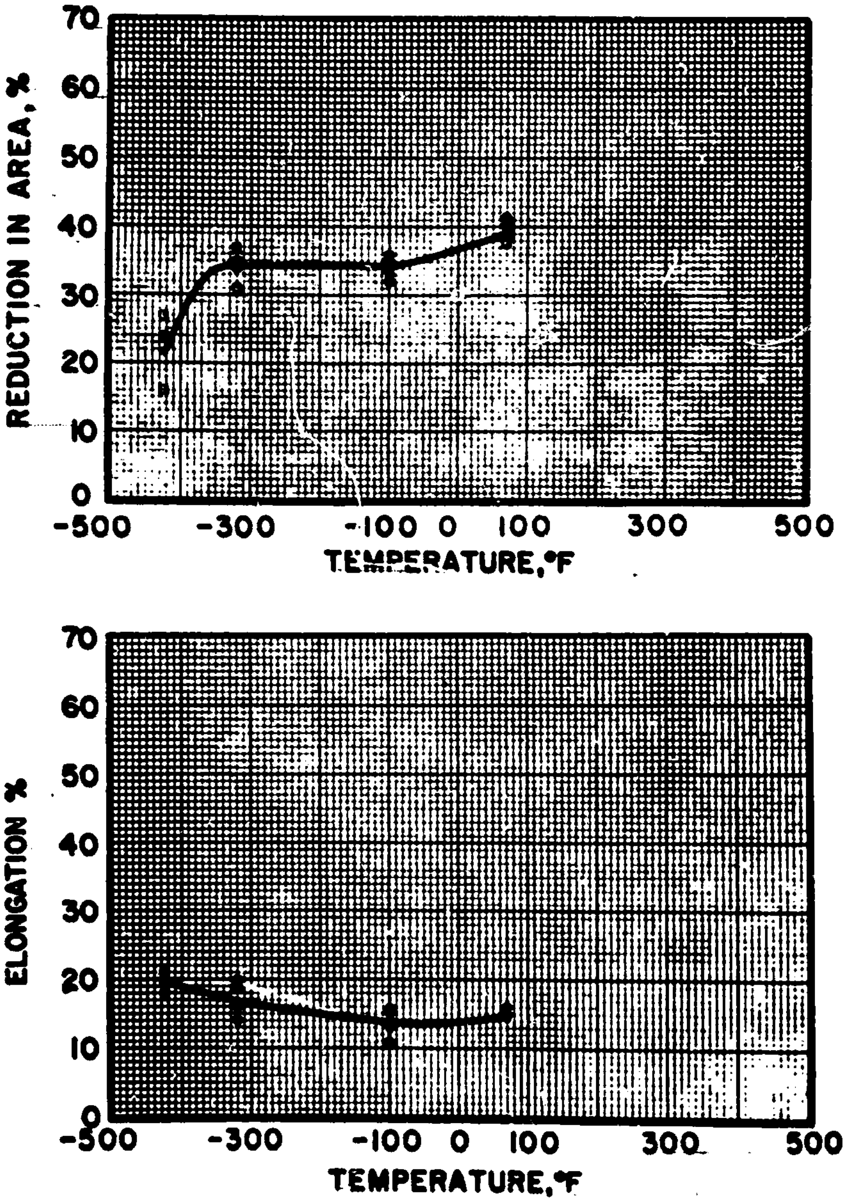
Titanium Alloy A-110-AT-ELI Forging (Heat D3272 Ring 220), Elongation and Area Reduction as a Function of Temperature

Figure 8



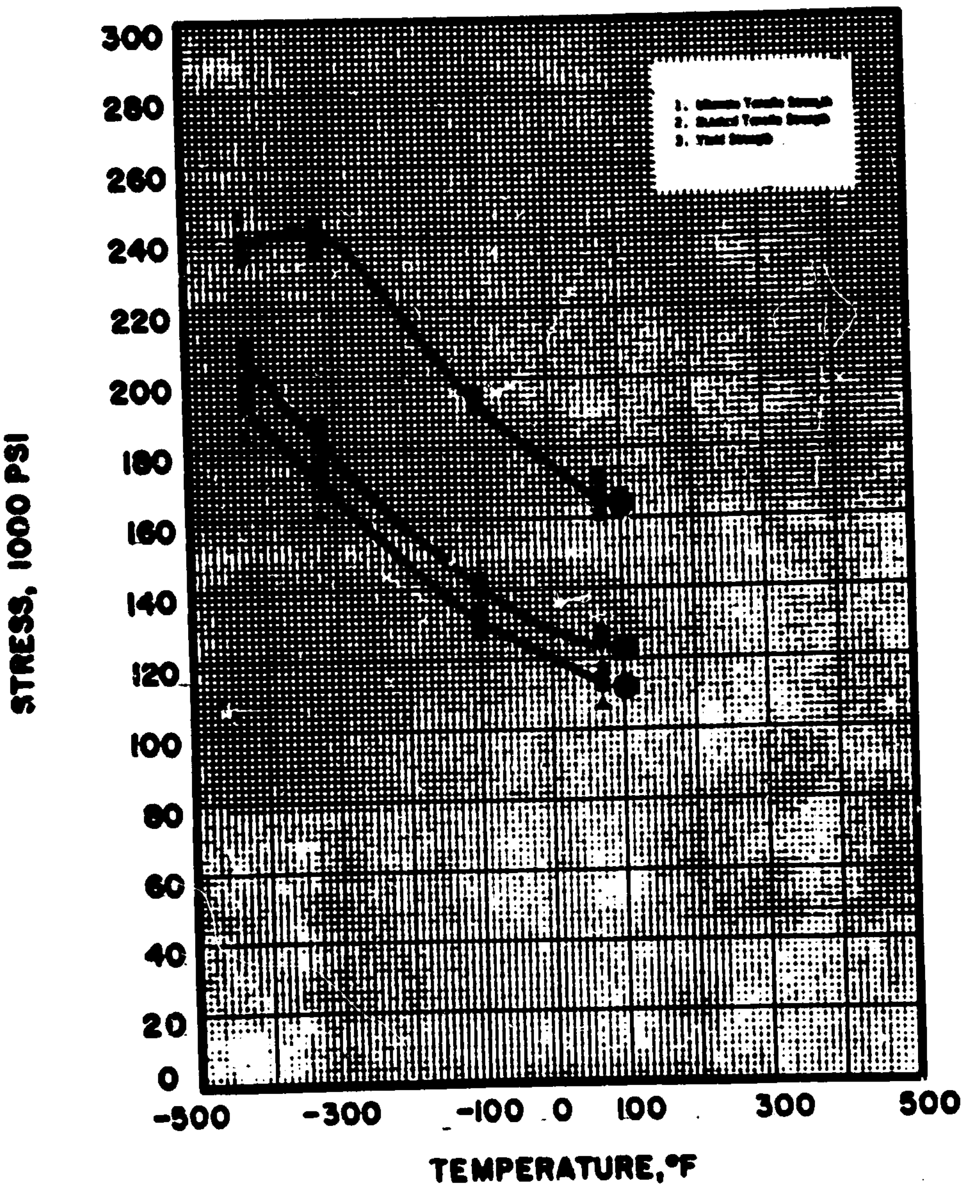
Titanium Alloy A-110-AT-ELI Forging (Heat 3346 Ring No. 217)
and Circumferential Direction, Tensile Ultimate, Yield
and Notched Strength as a Function of Temperature

Figure 9

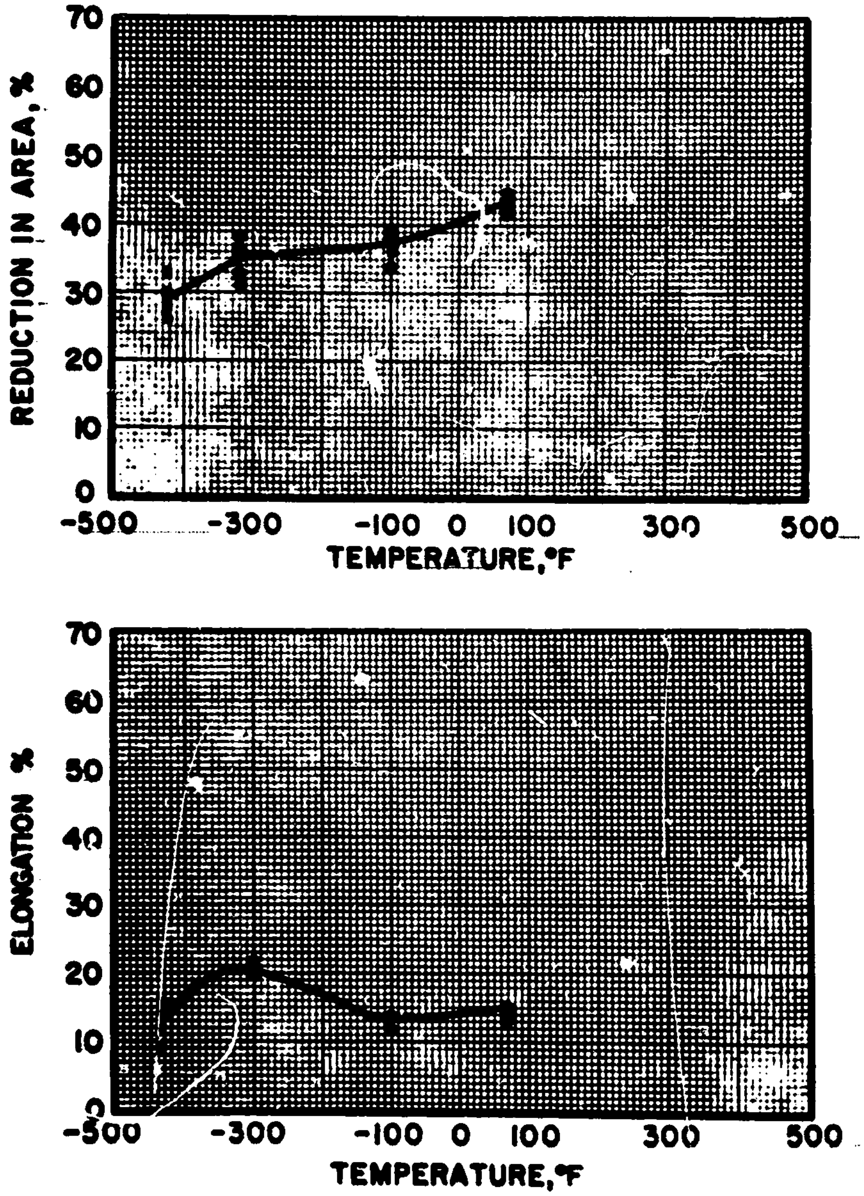


Titanium Alloy A-110-AT-ELI Forging (Heat 3346 Ring No. 217)
Circumferential Direction, Elongation and Area Reduction as a Function
of Temperature

Figure 10

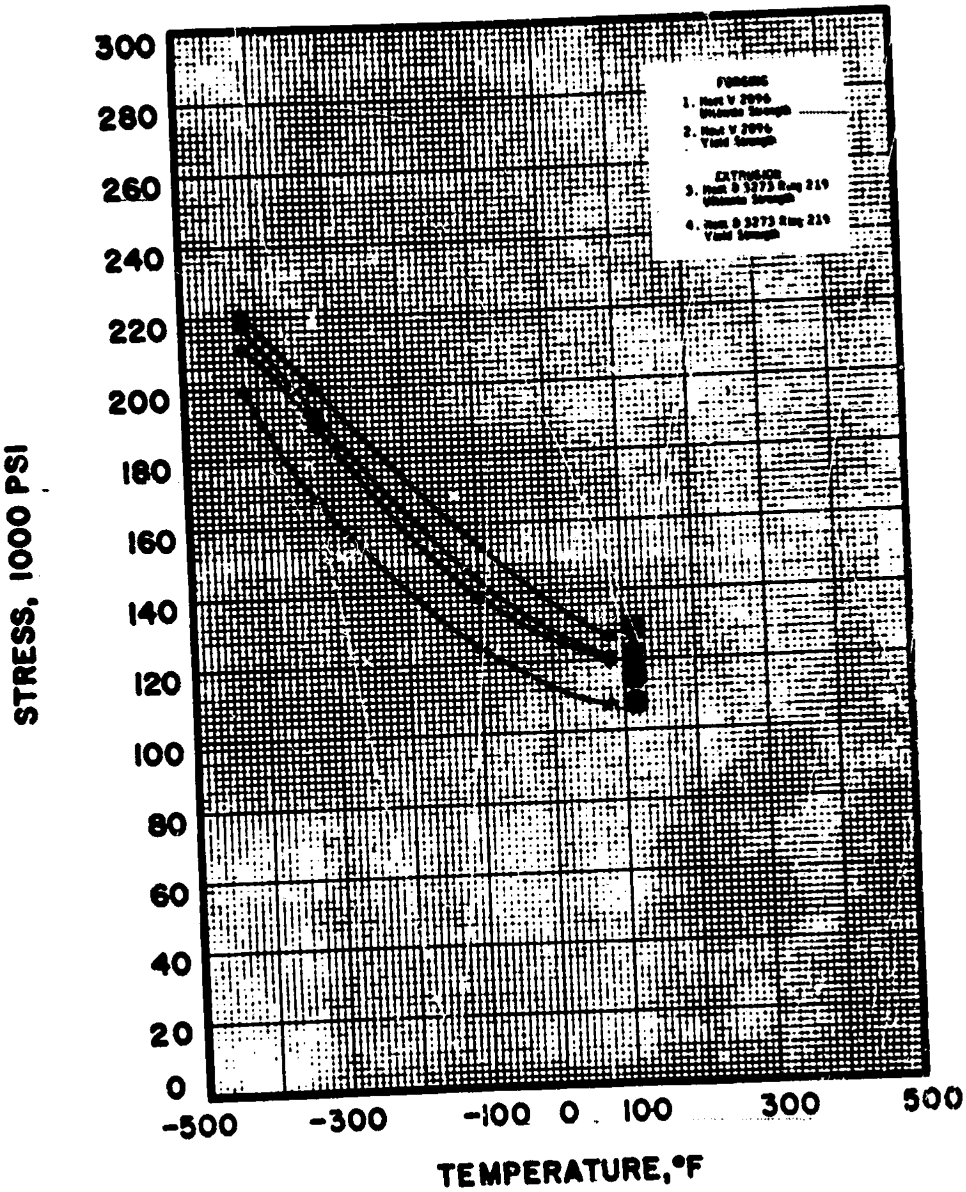


Titanium Alloy A-110-AT-ELI Extrusion (Heat 5273 Ring No. 218) Circumferential Direction, Tensile Ultimate, Yield and Notched Strength as a Function of Temperature



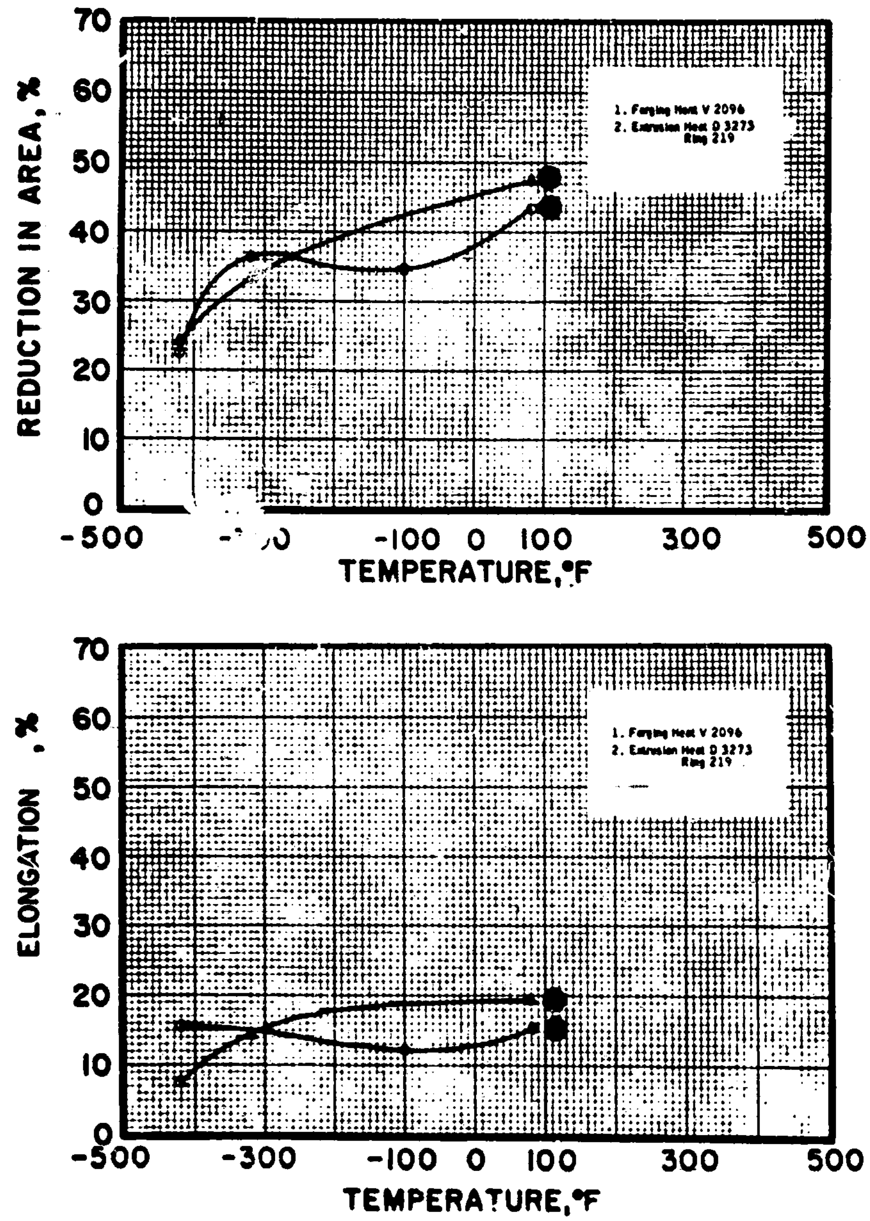
Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring No. 218)
Circumferential Direction, Elongation and Area Reduction
as a Function of Temperature

Figure 12



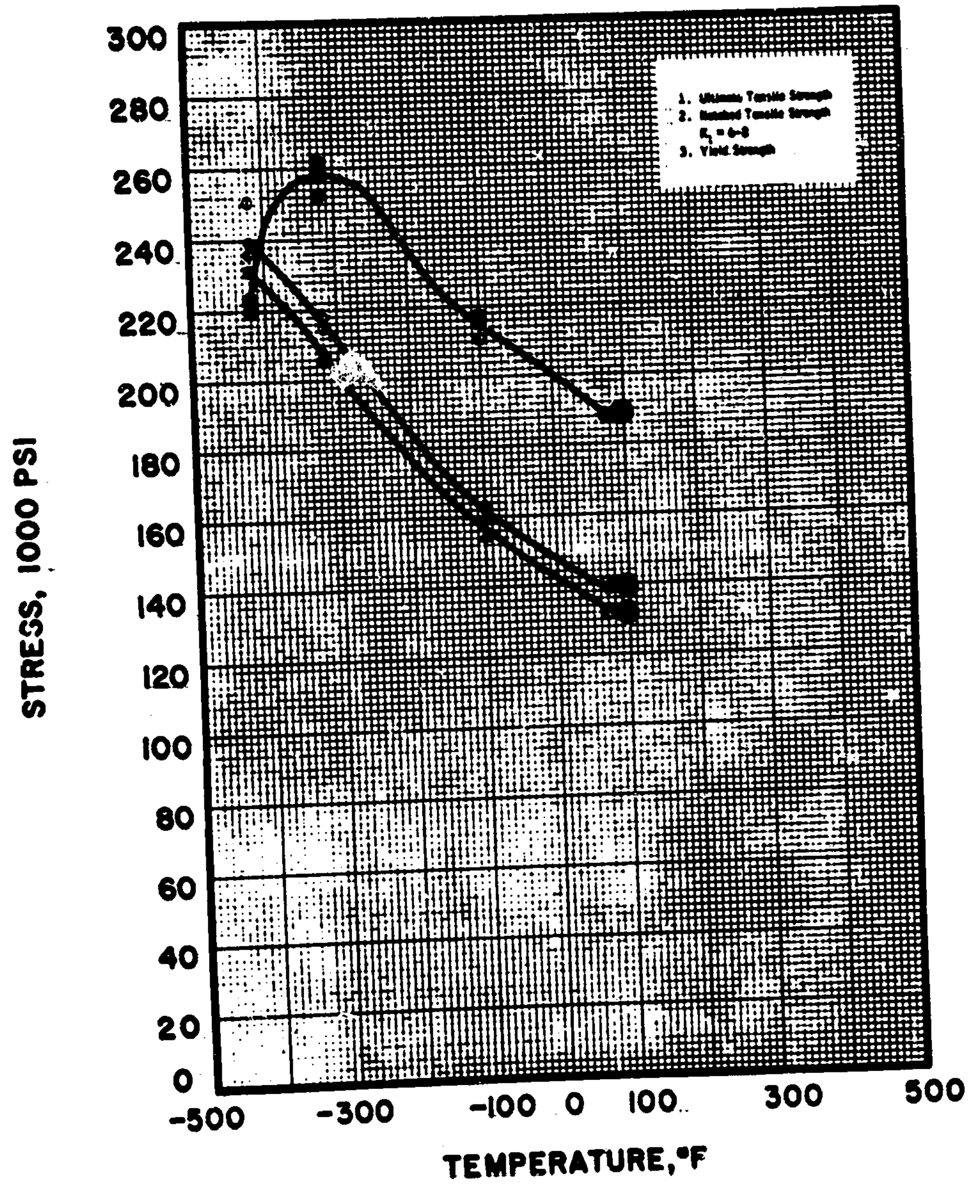
Titanium Alloy A-110-AT-ELI Comparison, Forgings and Extrusions
Longitudinal, Tensile Ultimate and Yield Strength
as a Function of Temperature

Figure 13



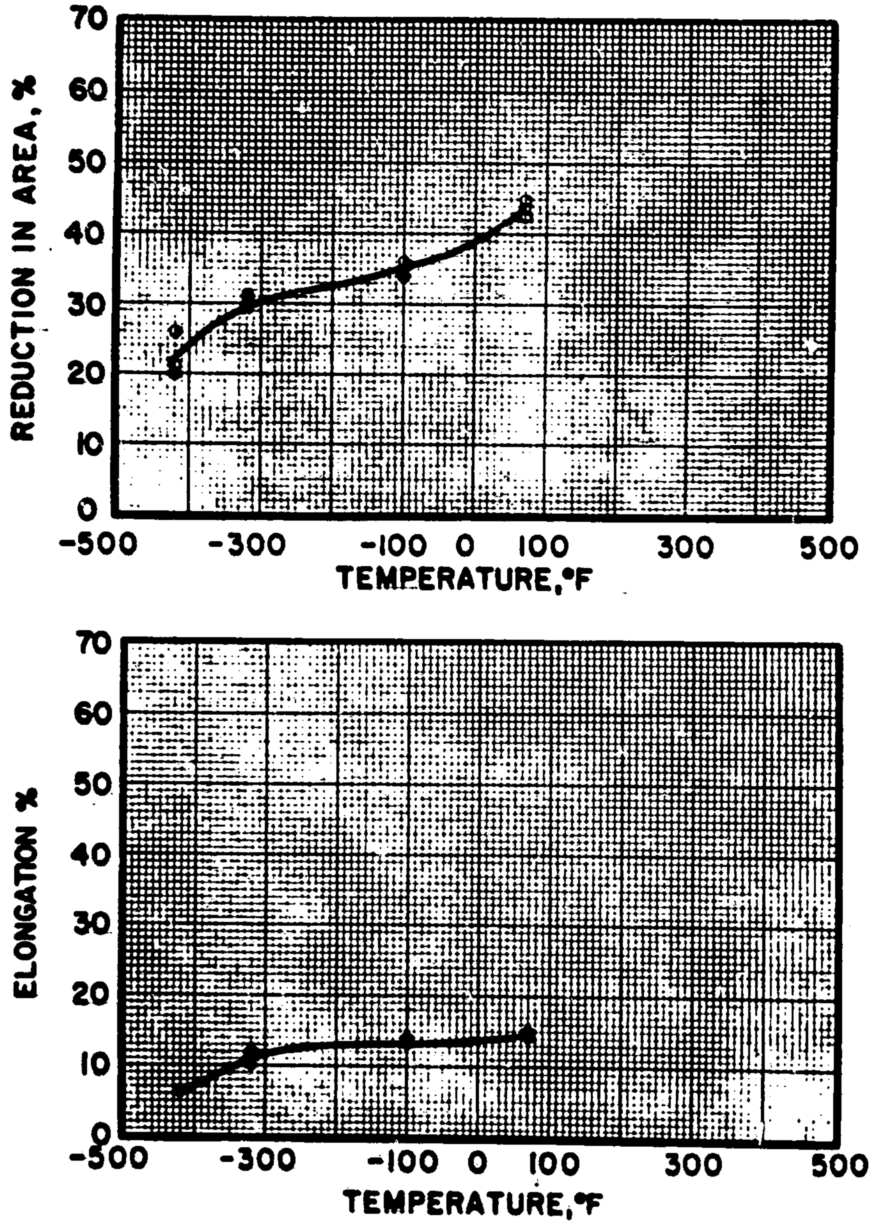
Titanium Alloy A-110-AT-ELI Comparison, Forgings and Extrusions
Elongation and Area Reduction as a Function of Temperature

Figure 14



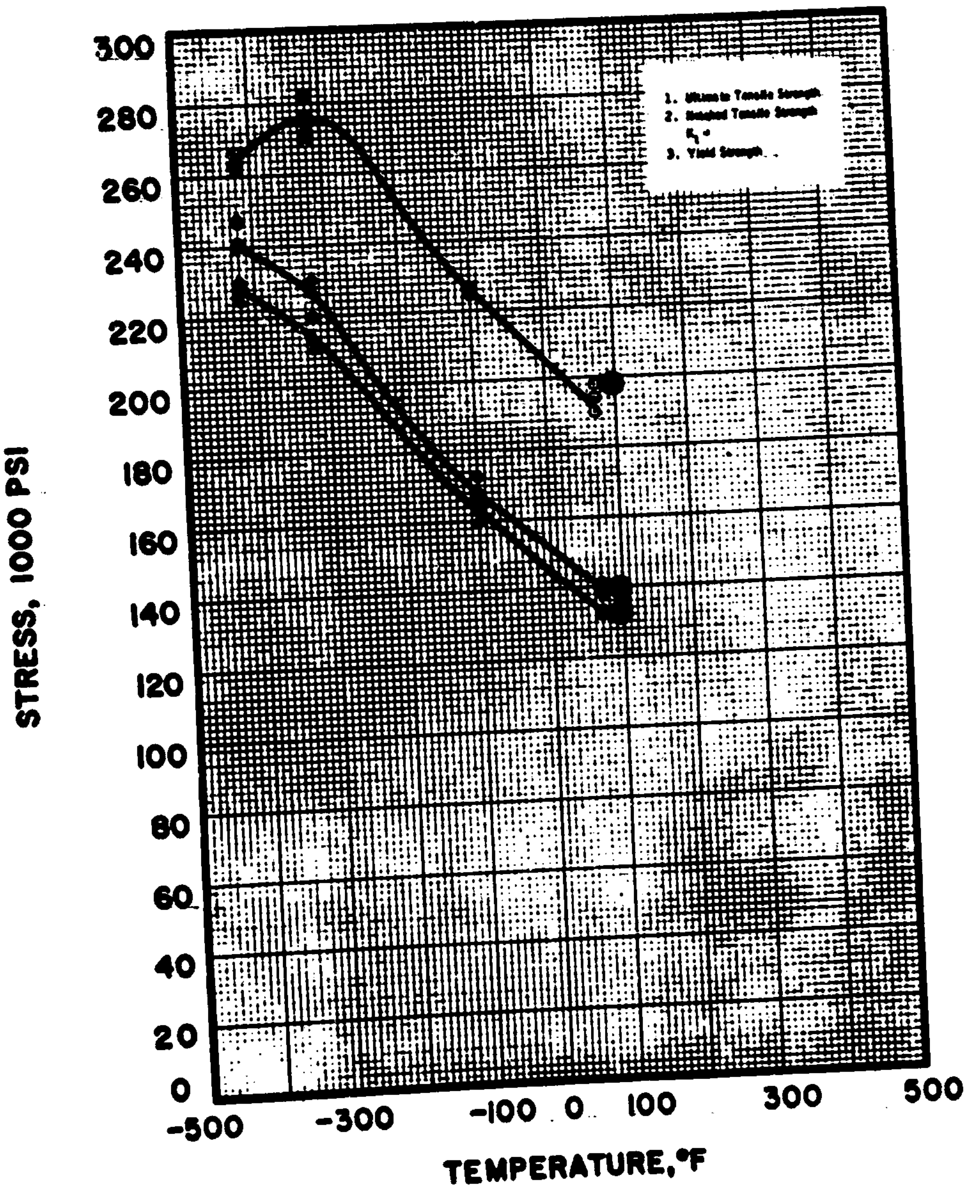
Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067), Transverse
Tensile Ultimate, Yield and Notched Strength
as a Function of Temperature

Figure. 15



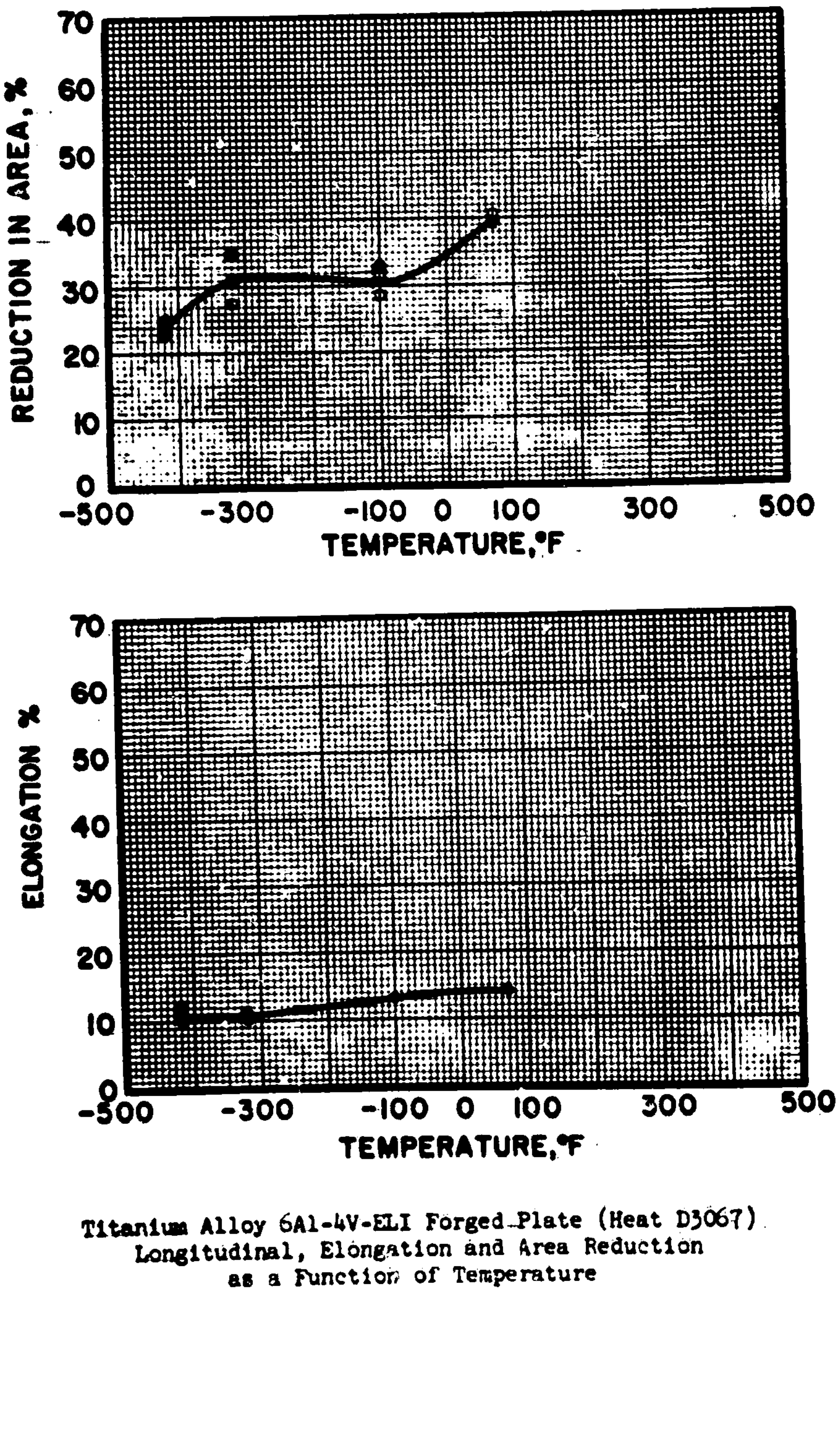
Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067), Transverse Elongation and Area Reduction as a Function of Temperature

Figure 16



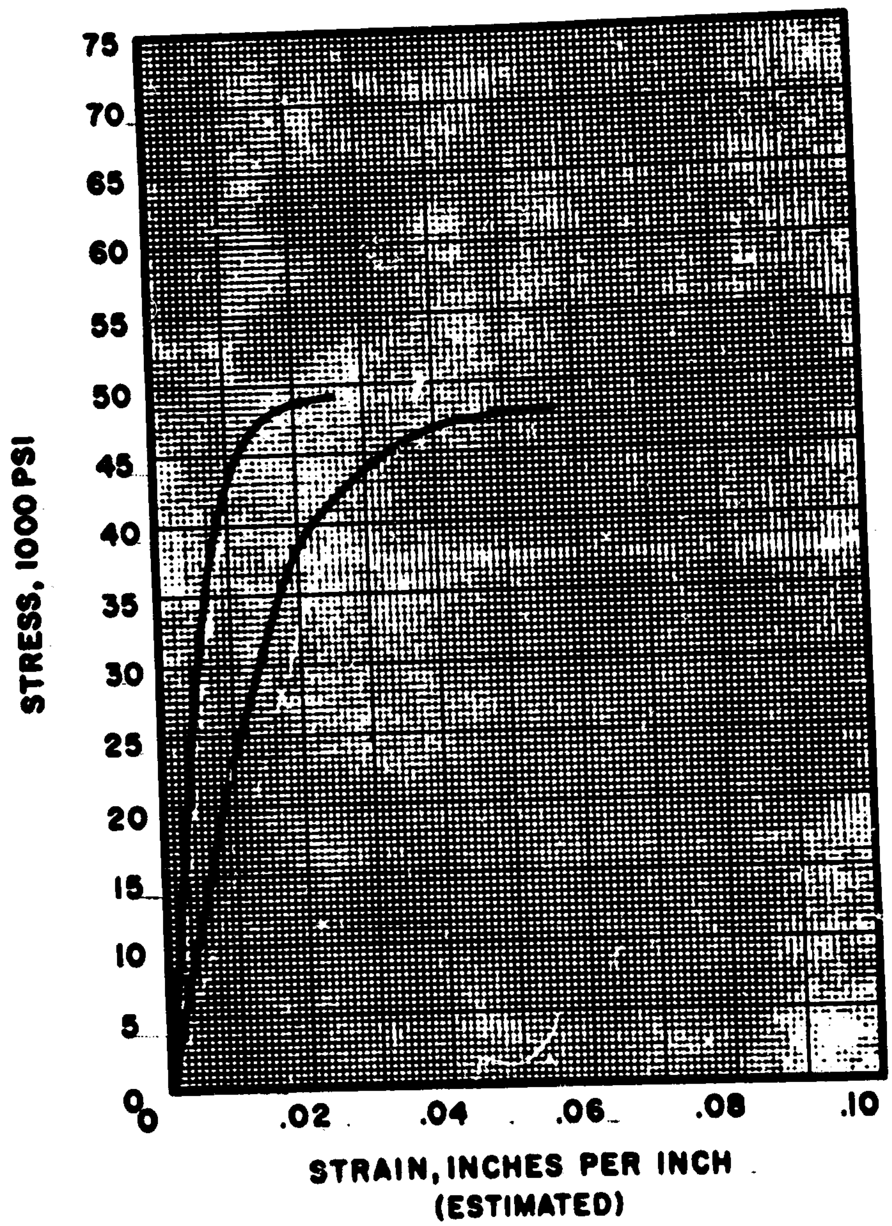
Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067),
Longitudinal, Ultimate Tensile, Notched and Yield Strength
as a Function of Temperature

Figure 17

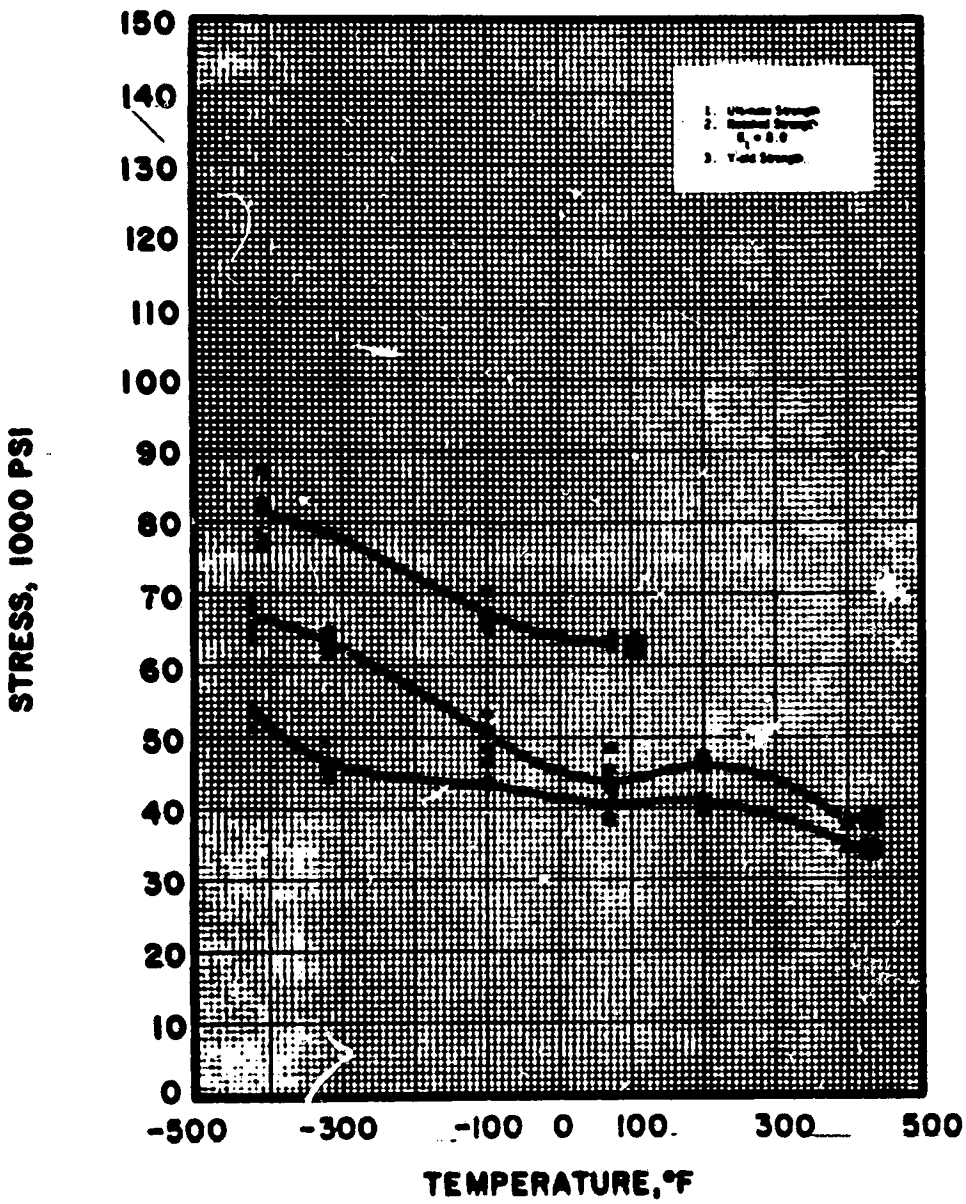


Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067)
Longitudinal, Elongation and Area Reduction
as a Function of Temperature

Figure 18

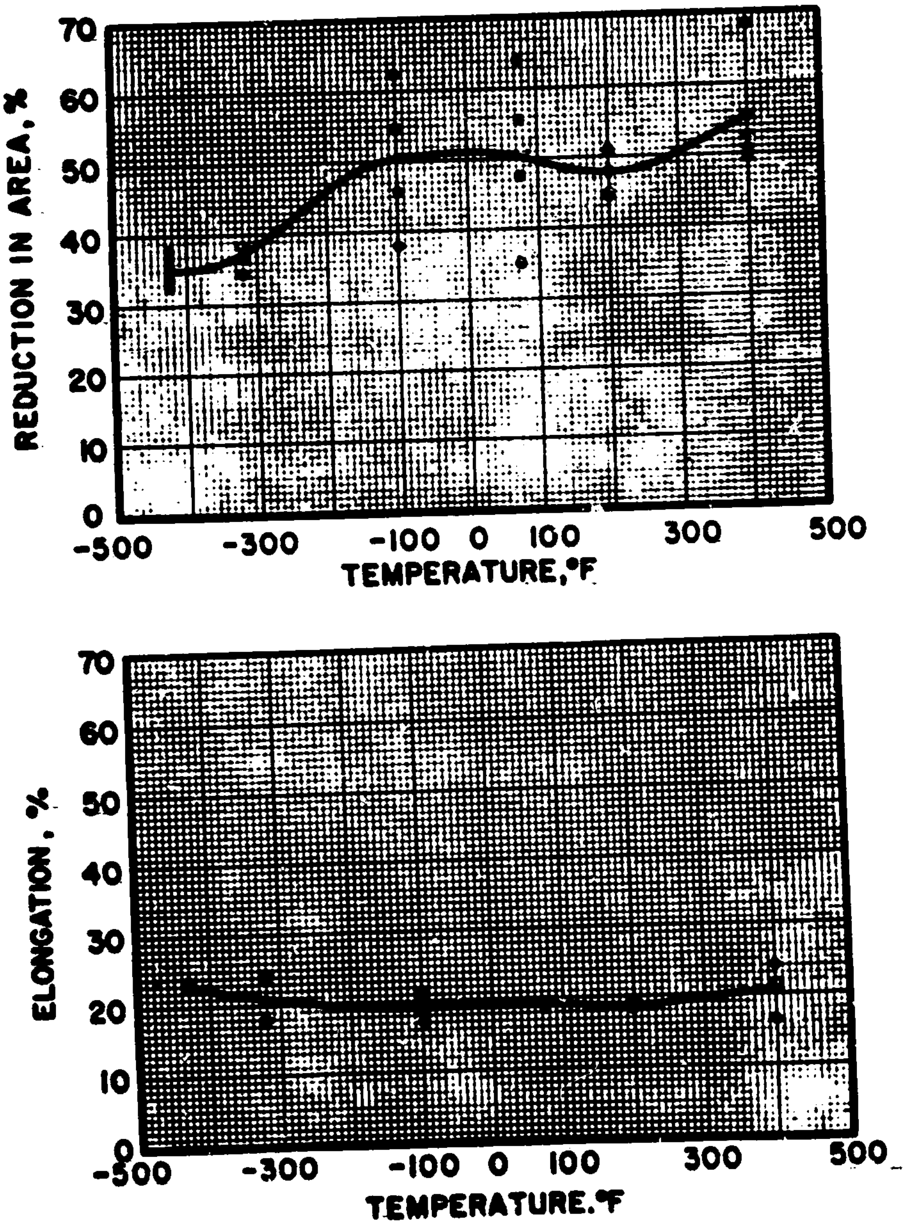


Aluminum Alloy A-356-T6, Stress-Strain Diagram
(at -423°F)



Aluminum Alloy 6061-T6 Forging, Tensile Ultimate, Yield and Notched Strength as a Function of Temperature

Figure 20



Aluminum Alloy 6061-T6 Forging - Elongation and Area Reduction as a Function of Temperature

Figure 21